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VCE TESTBED PROGRAM

PLANNING AND DEFINITION STUDY FINAL REPORT

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FOREWORD

This report summarizes the work performed under the Planning and Definition Study of the present NASA-sponsored VCE Testbed Program (Contract NAS3-20048). The NASA Project Manager for this study was Mr. A G. Powers. Mr J S. Westmoreland was the Pratt & Whitney Aircraft Program Manager with Mr. J Godston as Deputy Program Manager.

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PLANNING AND DEFINITION STUDY

SECTION 1.0

SUMMARY

This study provided definition and plans for a test program to demonstrate a low noise co-annular nozzle and a low emissions duct burner in a large-scale, Variable Cycle Engine (VCE) environment. This Planning and Definition Study consisted of the following three technical tasks updating the VSCE concept, defining the testbed design, and formulating the overall program plan.

VSCE Concept Update

The Variable Stream Control Engine (VSCE) was selected as the advanced supersonic flight engine concept for this study The baseline configuration incorporates numerous advanced-technology components, including a low-emissions duct burner and a coannular exhaust nozzle. The engine update involved revising the baseline design to reflect technical improvements in the duct burner and nozzle from related VCE technology programs

The duct burner was updated to a three stage system from a two stage system This concept is based on the Vorbix combustion technology that was demonstrated during the NASA/P&WA Experimental Clean Combustor Program This design has the potential to meet the performance and emissions requirements for future supersonic aircraft The selected design also meets the pressure loss, thrust efficiency, and ignition goals, and is considered as a moderate risk approach consistent with the large scale engine demonstration in calendar year 1978

The coannular exhaust nozzle in the updated VSCE is unchanged from the baseline configuration. It has a nominal 0 8 radius ratio in the outer fan stream and a plugless geometry in the inner core stream

Using the updated flight configuration, analytical predictions of performance, including noise and emissions, were updated. Also, the engine weight and length estimates were updated Results showed that baseline fuel consumption characteristics remain unchanged, and weight increase of 2.5 percent was incurred because of the three stage duct burner In terms of environmental factors, there was about a 2 EPNdB reduction in noise because of a more exact application of model test data. There was also no significant change to emissions estimates

Testbed Design Definition

The testbed system was designed to provide a large-scale demonstration of the two critical technology components, the duct burner and coannular nozzle In the Planning and Definition Study, the conceptual mechanical configuration and preliminary aerothermal design of the testbed system were established Also the definition of critical areas required to determine design criteria, estimates of performance, and preliminary control system and instrumentation requirements were established.

As part of the design definition, the F100 engine was selected as the gas generator for the testbed The F100 engine, in comparison to the other engines evaluated, has the best potential to simulate the desired exhaust conditions of the VSCE flight concept Furthermore, it does not require extensive modification for the testbed, which incorporates the duct burner, an existing F401 exhaust nozzle, and an ejector that can accommodate both a hard-wall surface and acoustic treatment

The major component subsystems in the testbed were reviewed from a thermal-mechanical standpoint in order to identify potential design problem areas resulting from integration of the F100 engine with the testbed This review encompassed the engine/testbed interface, the duct burner, nozzle, and ejector Also, assembly considerations were addressed and a mounting scheme was defined for installing the testbed system in the appropriate test facilities

Instrumentation requirements were defined to ensure meaningful and valid test data would be acquired during the planned test program The types of sensors, specific instrumentation for noise and emissions, safety, control, and health of the F100 engine were defined.

Test sites for conducting the test program were evaluated and selected To meet the program objectives three different sites will be employed Calibration of the F100 engine will be performed at the Pratt & Whitney Aircraft Government Products Division in Florida A checkout of the engine testbed system will be conducted at the Pratt & Whitney Aircraft Commercial Products Division in Connecticut. The Boeing Boardman facility in Oregon was selected as the site for conducting the aero/acoustic testing.

Overall Program Plan

The overall program plan, as outlined from this study, provides for a comprehensive evaluation of the duct burner and coannular nozzle The scope of work includes the necessary analytical effort to complete the testbed design, fabrication, procurement of test hardware, test program, data reduction and analysis

The program plan for testing the VCE testbed system covers a two-year period to complete two series of tests The first series of tests, which includes the aero/acoustic noise evaluation and associated preparation tests, is scheduled for completion by the end of calendar year 1978 After this demonstration of the coannular noise benefit, a second series of tests is planned to obtain duct burner emissions and performance data. The testing includes an evaluation of the initial duct burner configuration, the testing of one minor and one major duct burner modification, and a second aero/acoustic evaluation using the refined duct burner configuration This work will be conducted during the 1979 and 1980 calendar years

SECTION 2.0

INTRODUCTION

Propulsion systems designed for second-generation supersonic commercial aircraft must achieve improved fuel economy during both subsonic and supersonic flight conditions, while operating within the environmental constraints of reduced exhaust emissions and reduced noise levels In recent studies completed by Pratt & Whitney Aircraft, the area of main interest has focussed on the study of the Variable Cycle Engine (VCE) concept Basically, the VCE concept uses inflight cycle changes to optimize propulsive efficiency in both subsonic and supersonic flight regimes

The study of the VCE concept has proceeded primarily on an analytical basis under several NASA-sponsored programs. This work has identified the Variable Stream Control Engine (VSCE), a derivative of the VCE, as one of the most attractive approaches to meet the requirements of future supersonic aircraft. The VSCE uses two key components, a low-emissions duct burner and a coannular exhaust nozzle, to offer substantial gains in emissions and noise reduction along with increased range, when compared to technology available today

At present, model testing of the coannular nozzle as well as rig testing of the duct burner are in progress under NASA-sponsored VCE-related programs (NAS3-20061 and NAS3-20602, respectively)

Demonstrating the environmental advantages of the duct burner and coannular nozzle is the principal objective of the current NASA-sponsored VCE Testbed Program The Testbed Program is a multiphase effort that, as planned, will culminate in a large scale demonstration of these components at operating conditions representative of the VSCE.

The work completed in the initial phase of the Testbed Program, which is the subject of this report, involves the planning and definition of the overall program. The three major tasks completed as part of the planning and definition of the VCE Testbed Program are the VSCE Concept Update, Testbed Design Definition, and Testbed Program Plan, as shown in Table 2 0-I.

TABLE 2.0-I

VCE TESTBED PLANNING AND DEFINITION STUDY

Update VSCE concept	Testbed design definition	Testbed program plan

• Integration studies
• VCE component programs
• Update
  • Weight
  • Noise
  • Emissions
  • Range
	• Experimental components
	• Select testbed engine
	• Select variable nozzle hardware
	• Select duct burner
	• Configuration
	• Mount concept
	• Instrumentation
	• Controls
	• Performance simulation
		• Test matrix
		• Facilities
		• Schedule
		• Cost
		• Long lead time hardware

SECTION 3.0

RESULTS OF STUDY AND CONCLUSIONS

3.1 SCAR STUDY VCE CONCEPT AND UPDATE

This study involved updating a flight engine definition of the VCE concept in order to provide a current baseline engine for planning the VCE Testbed Program. The engine concept selected for this study is the VSCE-502B, and a cross section of the conceptual mechanical configuration is shown in Figure 3 1-1. The VSCE-502B is dual spool turbofan utilizing far-term technology advances in the areas of structures, aerothermodynamics, and materials to meet the stringent environmental and performance standards for future supersonic commercial aircraft.

The two critical components in the engine are a low-emissions duct burner and a coannular exhaust nozzle In this study, the baseline VSCE was updated to reflect design improvements with these two components.

Under a related NASA-sponsored technology program, Pratt & Whitney Aircraft has been conducting model tests of different coannular nozzle geometries. On the basis of results acquired to date, the nozzle configuration illustrated in Figure 3.1-1 has been selected for the flight engine. As part of another NASA-sponsored technology program, various duct burner concepts were assessed analytically in terms of performance, emissions, and general compatibility with the requirements with the VSCE-502B. From the results of this work, a three stage duct burner system, based on the Vorbix combustion technology, was selected. The designs of both of these components met the performance goals of the flight engine and are consistent with the flight engine schedule.

Incorporating these improved component designs in the baseline flight engine adds only a slight weight increase. However, the overall engine length and diameter remain unchanged.

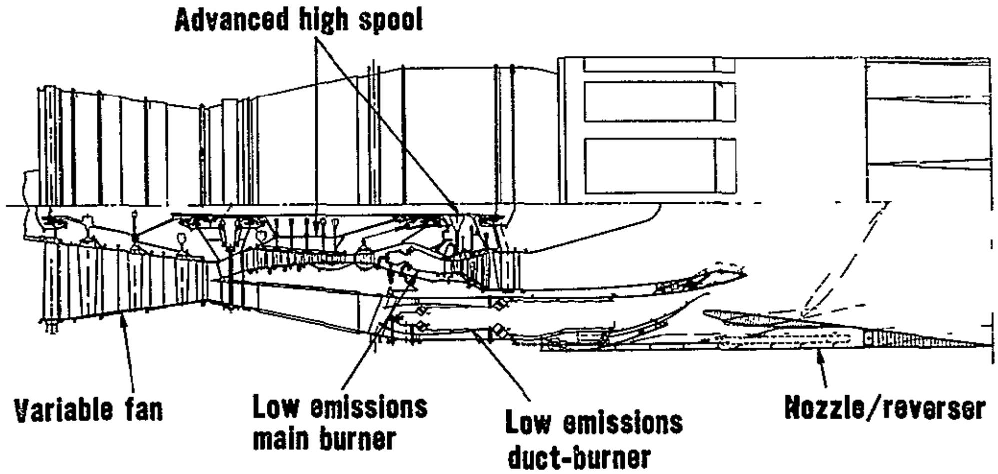


Figure 3.1-1 VSCE-502B – The two critical components in this engine concept are the low-emissions duct burner and the coannular exhaust nozzle

The added weight, which amounts to approximately 105 kgs (230 lbs), is attributed to the third combustion stage in the duct burner and associated hardware. Through further technology development, it may be possible to negate this weight penalty.

Overall engine performance is unaffected by the component changes In fact, fuel consumption estimates for the VSCE-502B are the same for both subsonic and supersonic cruise conditions as initially estimated during Phase IV of the Advanced Supersonic Propulsion Studies (Reference 1).

Engine exhaust emissions and noise levels were also re-examined. Emissions levels were updated to reflect the improved duct burner configuration and the addition of recent emissions data from the NASA/P&WA Experimental Clean Combustor Program. Figure 3.1-2 presents the Environmental Protection Agency Parameter (EPAP) for the airport vicinity for the VSCE-502B based on ECCP data extrapolated to the operating characteristics of the main and duct burner. As indicated, a higher duct burner efficiency is required to meet the EPA carbon monoxide rule for advanced supersonic engines. The control of other pollutants is very close to the 1984 EPA rule.

Figure 3.1-2 Updated Emissions Estimates – A duct burner efficiency of 99.6 percent is required to meet the 1984 EPA carbon monoxide rule for advanced supersonic engines.

1 - R A. Howlett and F. D. Streicker, "Advanced Supersonic Propulsion Study Phase IV Final Report",. NASA CR-135273, September 1977

Initial noise estimates were updated using refined prediction procedures to account for other noise generating components, in particular the turbine and duct burner. Figure 3.1-3 presents a comparison of the original and updated noise predictions at full throttle maximum duct burning flyover conditions. The coannular acoustic benefit has been included in these predictions at full throttle maximum duct burning conditions. The coannular acoustic benefit has been included in these predictions

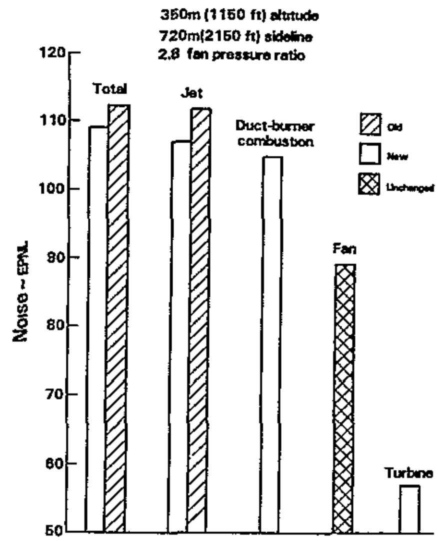


Figure 3 1-3 Updated Noise Estimates – Using the added prediction procedures, overall noise levels are lower for the updated VSCE-502B

The impact of technology on the VSCE cycle definition was evaluated in a parallel NASA program by defining an engine, the VSCE-511, based on nearer term levels of material and component technology. A comparison of the nearer term engine with the far-term VSCE-502B indicates that the combination of reduced cycle temperatures, reduced cycle pressures, and lower material stress levels causes an approximate 7 percent penalty to aircraft range. The cycle characteristics of each technology level VSCE are such that both will draw design information for the coannular nozzle and duct burner from the VCE component and testbed programs.

3.2 VCE TESTBED DESIGN DEFINITION

The main objective of the Testbed Program is to experimentally evaluate, in an operating environment representative of the Variable Stream Control Engine, the noise benefit produced by the interaction of the low-emissions duct burner and coannular exhaust nozzle The testbed design approach is to provide a realistic and large-scale demonstration of these two critical technology components by using an advanced, current-technology F100 engine as the gas generator

Of the different Pratt & Whitney Aircraft engines evaluated for use in the Testbed Program, the F100 has the most potential to approximate the desired exhaust conditions of the VSCE-502B as well as the near-term technology engine, the VSCE-511 The cycle characteristics of the rematched F100 engine are presented in Table 3 2-I along with the VSCE-502B and -511 cycle characteristics for comparison. Other considerations for selecting the F100 engine are that the engine does not require extensive modification for integration of the testbed, and it provides the highest level of duct burner airflow of all the available Pratt & Whitney Aircraft engines so the maximum annulus height for the duct burner is obtained

A cross-sectional view of the VCE testbed configuration, including the F100 engine, is shown in Figure 3.2-1. The testbed replaces the F100 mixed-flow afterburner and supersonic exhaust nozzle with a three-stage Vorbix duct burner, a F401 nozzle, and an acoustically-treated ejector. The duct burner has independent metering of fuel flows to the three combustion zones to permit an evaluation of the coannular noise effect at simulated takeoff, subsonic cruise, and part power conditions. The different testbed components will be manufactured from conventional materials currently used in engine hot sections in order to reduce fabrication time and program cost.

TABLE 3 2 I

COMPARISON OF REMATCHED F100 CYCLE WITH VSCE-502B AND VSCE-511 CYCLES

Cycle	Far-Term VSCE-502B	Near-Term VSCE-511	Testbed (Rematched F100)
Fan Pressure Ratio (Design Level)	3 3	3 3	3 1
Overall Pressure Ratio	20	13 4	20 8
Bypass Ratio	1 3	0 85	0 91
Max S L S Combustor Exit Temp ~ °C (°F)	1204 (2200)	1093 (2000)	1204 (2200)
Fan Pressure Ratio	2 8 – 3 3	2 8 – 3 3	3 1
Exhaust Condition			
Velocity Ratio (Duct/Engine)	1 7	1 7	1 7
Nozzle Area Ratio (Duct/Engine)	1 0 – 1 4	0 7 – 1 1	0 79
Airflow Ratio (Duct/Engine)	1 3 – 1 5	0 8 – 1 1	0 93
Duct Burner Condition			
Inlet Temp ~ °C (°F)	143 – 153 (290 – 310)	143 – 153 (290 – 310)	152 (307)
Exit temp ~ °C (°F)	1148 – 1287 (2100 – 2350)	1287 – 1426 (2350 – 2600)	1165 (2130)
Pressure ~ N/m^2 (psia)	2 27 X 10^5 – 2 89 X 10^5 (33 – 42)	2 2 X 10^5 – 2 89 X 10^5 (32 – 42)	2 44 X 10^5 (35 5)
Fuel Air Ratio	0 03 – 0 035	0 036 – 0 042	0 031
Net Thrust ~ kgs (lbs)/Total Corrected Airflow ~ kg/sec (lbs/sec)	66 – 69	66 – 68	63 5

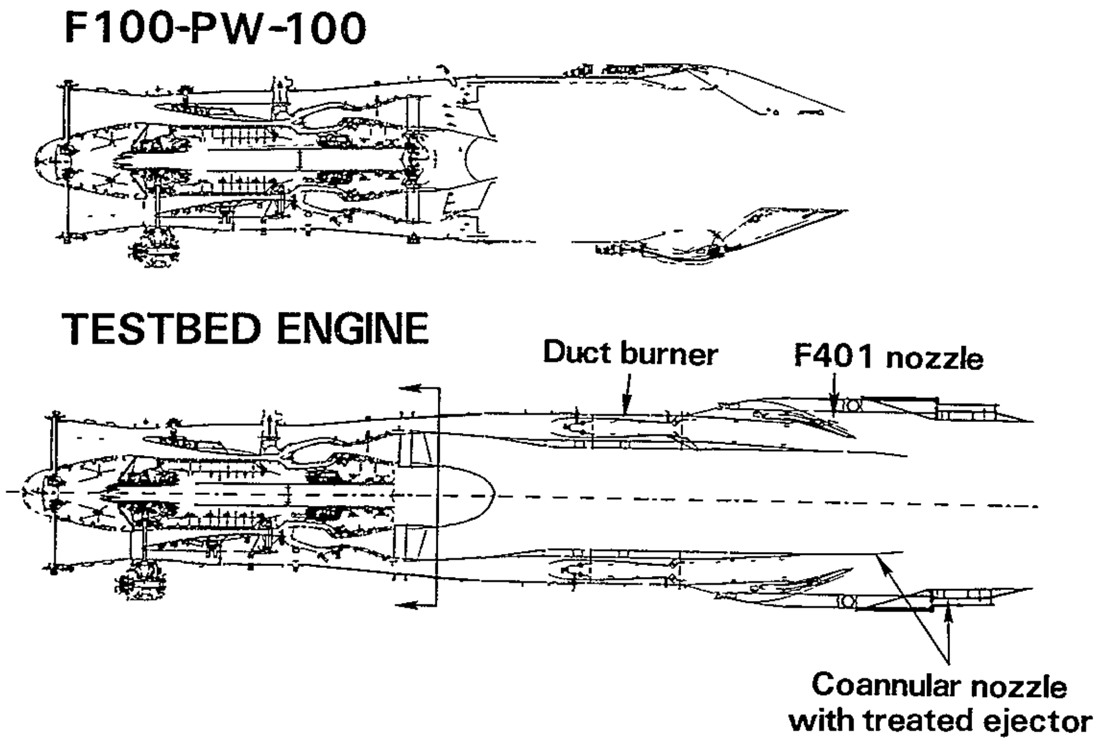


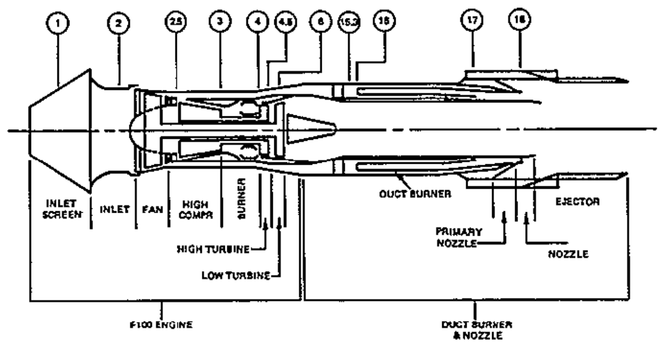
Figure 3 2-1 VCE Testbed Configuration – Adapting the testbed to the F100 engine allows testing at exhaust conditions which closely duplicate the VSCE-502B

In the Planning and Definition Study, work has progressed to the point where the conceptual mechanical configuration and preliminary aerothermal design definition have been established This includes definition of pertinent areas required to define design criteria, estimates of performance, and establish control system and instrumentation requirements Also, assembly considerations for the testbed have been addressed and a mounting scheme for installing the testbed engine in the test facility has been defined

An area of particular importance is the definition of test instrumentation requirements. These design requirements ensure that adequate data will be acquired to substantiate the design prediction system and to demonstrate the validity of data obtained in earlier scale model tests. This information will include data for determining levels of overall aerothermodynamic performance, emissions and noise Velocity profiles to measure the coannular effect at the fan stream and core stream exit planes will be acquired with a laser doppler velocimeter. Additional instrumentation to monitor safety of operation and engine control has been also provided in the definition of instrumentation requirements. Table 3 2-II presents a listing of the different type of instrumentation that is planned for the test phase of the program

TABLE 3.2-II

TESTBED INSTRUMENTATION SUMMARY



Station and Location		Probe Type	General Remarks
		Performance Instrumentation	
1	Inlet Screen	Temperature	Data used for energy balance calculation for duct burner inlet airflow determination and standard day corrections
2	Engine Inlet	Pitot-Static	Standard day corrections and calculations of total airflow
2 5	Fan Discharge	Temperature	Update performance simulation
		Pressure	Define and establish fan operating line
		Pitot-Static and average temperature	Data used to indicate fan pressure ratio to assist in setting test points
3	High-Pressure Compressor Discharge	Temperature and pressure	Update performance simulation and core airflow iteration technique
4 5	Fan Turbine Inlet	Temperature	Fuel control correction, provide engine data, and monitor engine operation
6	Fan Turbine Exit	Pressure	Core engine data define primary nozzle performance, engine monitoring, and energy balance calculation
		Temperature	Fan duct data define duct inlet conditions, duct burner efficiency calculations, and energy balance calculation for duct burner inlet airflow determination.

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TABLE 3.2-II (Cont'd)

Station and Location	Probe Type	General Remarks
15.9 Augmentor Duct	Pressure and temperature	Defines duct-burner inlet conditions and duct burner airflow determination
16.0 - 18.0 Duct Burner Area	Static pressure and metal temperatures	Duct burner performance diagnosis
16 0 - 18.0 Ejector Inlet and Flowpath	Static pressure	Nozzle performance diagnosis
15 9 16.3 Fuel Manifolds 16.5	Pressure and flow	Testbed performance
	Emissions instrumentation	
18.0 Fan Duct Nozzle (without ejector)	Temperature, pressure and emissions	Duct burner performance and emissions
18 0+ Primary Nozzle Exit (with ejector) and Ejector Exit	Emissions	Same probe used at ejector, exit and primary nozzle
	Acoustic instrumentation	
15 2 Augmentor Duct	Pressure (Kulites)	Measure noise at duct burner inlet
16.1 16.4 Duct Burner 16.5 16.9	Pressure (Kulites)	Define duct burner noise and detect burner screech
18.0 Ejector	Pressure (Kulites)	Defines ejector noise
18.0+ Ejector Exit	Velocity (LDV)	Defines velocity profiles
	Condition monitoring instrumentation	
2 Engine Inlet 16.6 Fan Duct Nozzle 16.9 Inner Duct 17.7 Ejector Inlet	Accelerometers	Measures vibration levels

3.3 PHASE II PROGRAM PLAN

Phase II of the VCE Testbed Program continues the work started in the Planning and Definition Study, and, as scheduled, will culminate with comprehensive aero/acoustic and emissions tests of the testbed system. Although the work outlined for Phase II is principally test oriented, it also encompasses completing the final design of the testbed and associated design analyses as well as fabricating and/or procuring test hardware

As defined during the current study, the test plan covers a two-year period and consists of the major elements shown in Figure 3 3-1 The first series of tests, ending with the aero/acoustic evaluation, will be completed during calendar year 1978. The first test in this series is a calibration of the F100 core engine, and will be conducted at the Pratt & Whitney Aircraft Government Products Division in Florida Next, a checkout of the integrated F100 testbed system will be completed at the Pratt & Whitney Aircraft Commercial Products Division in Connecticut Aero/acoustic testing, which comprises the main portion of the test program, will be conducted at the Boeing Boardman facility in Oregon. The facilities used to conduct each test were specifically selected during the Planning and Definition Study on the basis of criteria which reflect adequacy to support the test program from both technical and logistic standpoints

The second series of tests involves the emissions evaluation As indicated in Figure 3.3-1, this test is planned for the 1979 calendar year. Testing will be conducted at the Pratt & Whitney Aircraft Commercial Products Division with additional aero/acoustic testing to be conducted at the Boardman site

The overall schedule of the NASA-sponsored VCE Testbed Program is presented in Figure 3 3-2 This schedule indicates the work that has been completed under the current Planning and Definition Study and the work recom-

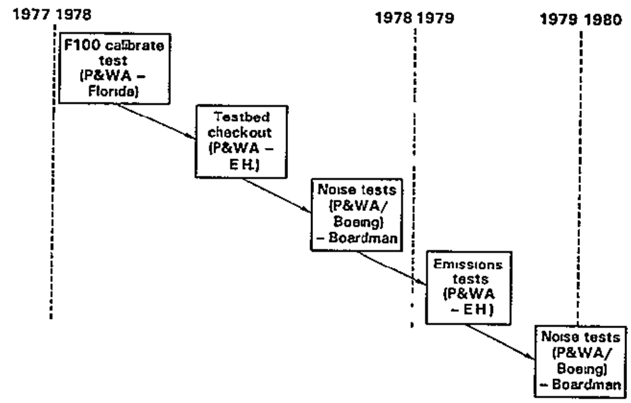

Figure 3 3-1 VCE Test Plan – The test plan, as defined, provides a comprehensive, large-scale evaluation of the duct burner and coannular nozzle with a particular emphasis on low risk

mended, basically the aero/acoustic and emissions tests, for demonstrating the technology readiness of the low-emissions duct burner and the coannular exhaust nozzle. This schedule also takes into consideration the appropriate interfaces with the other VCE-related technology programs.

3.4 CONCLUSIONS AND RECOMMENDATIONS

From the work completed in the Planning and Definition Study, the following general conclusions have been made.

- On the basis of NASA-funded integration studies by the engine/airframer contractors, the Variable Stream Control Engine (VSCE) was identified as the most promising concept for a supersonic application, and was therefore selected as the baseline flight engine definition for the VCE testbed.

- The testbed system, using the F100 engine as the gas generator, is a viable method to experimentally evaluate, in large scale, the coannular noise effect and the interactive performance and emissions characteristics of the duct burner

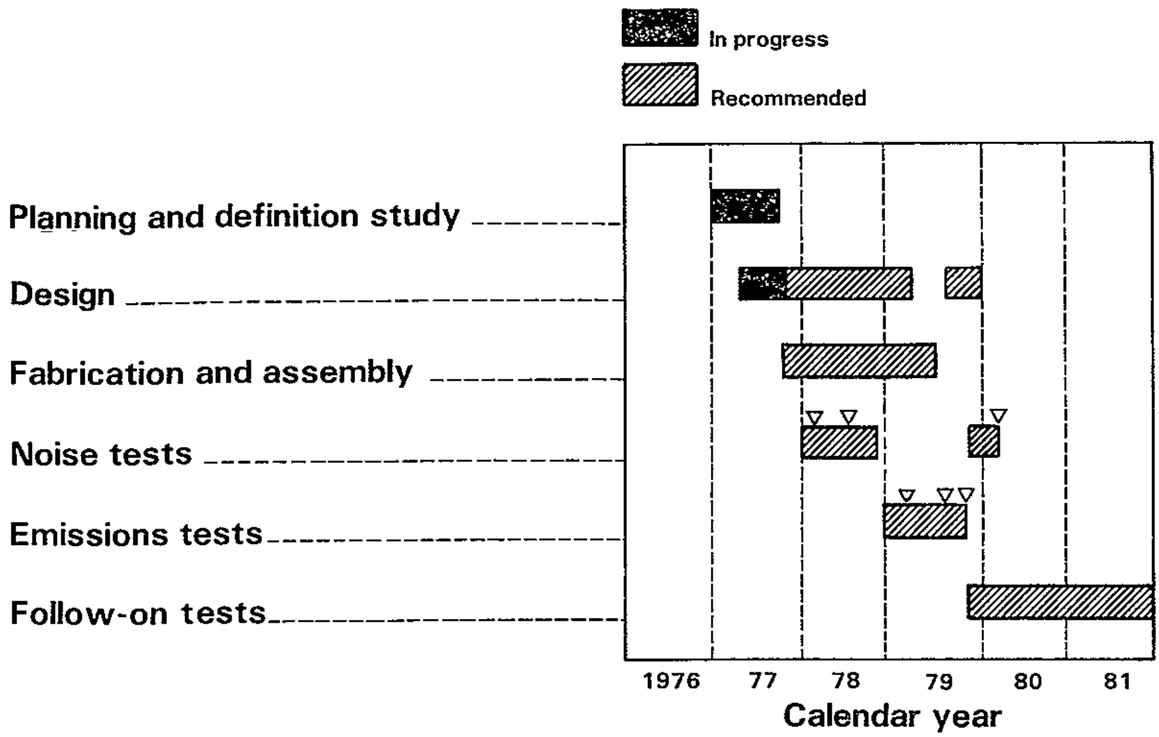

Figure 3 3-2 NASA/P&WA VCE Testbed Program Schedule – The overall program schedule has allowances for follow-on testing to evaluate other technology areas requiring further work

- The program plan recommended for the Phase II aero/acoustic and emissions tests is structured to minimize program risk and ensure a comprehensive test to provide data to verify the technology demonstrated in scale model tests The test plan is time-phased to utilize information from other NASA VCE-related technology programs for the duct burner and nozzle.

Based on these conclusions, the recommendation is to proceed with the planned VCE Testbed Program to ensure continuous progress in the testbed and coannular and duct burner technology programs leading to a total engine technology demonstration as part of the Variable Cycle Experimental Engine Program

Possible follow-on programs using the basic VCE testbed system are to evaluate flight effects on the coannular noise benefit in the NASA-Ames 13.6-by-27 meter (40 by 80 foot) wind tunnel Other possible programs include inlet noise/performance tests, a more refined nozzle test with evaluation of a thrust reverser, and, depending on the noise test results as well as future noise requirements, jet noise suppression tests in which the suppressor would be applied only to the outer, high velocity stream of the coannular nozzle.

SECTION 4.0
DISCUSSION OF RESULTS

4.1 SCAR STUDY VCE CONCEPT AND UPDATE

4.1.1 Introduction

Updating a study Variable Cycle Engine (VCE) concept was the first of three technical tasks completed in this program. The purpose of this task was to select the most promising VCE concept and revise the mechanical design and performance predictions to reflect design improvements in key components defined in related technology programs. As discussed in the following section, the Variable Stream Control Engine (VSCE) was selected as the study engine. In this particular engine configuration, the critical components are a low-emissions duct burner and a low-noise exhaust nozzle.

Concurrent with the VCE Testbed Planning and Definition Study, the duct burner and coannular nozzle designs were refined under two NASA-sponsored component technology programs*. As design perturbations were evaluated, the study engine was updated analytically to reflect configuration and performance changes obtained through component optimization. Updating the performance included updating both noise and exhaust emissions estimates. In addition, engine weight, critical dimensions, and installation requirements were modified to reflect updated component technologies. Using the final version of the study engine, the engine size requirements and aircraft range were determined according to established ground rules

*Contract NAS3-20602, Low-Emissions Duct Burner for F100 Component Testbed Engine Program

Contract NAS3-20061, Aero/Acoustic Performance of a Coannular Exhaust Nozzle for Variable Cycle Engines

4.1.2 Engine Design Definition

4.1.2.1 Study Engine Concept

Selection of the VSCE as the baseline engine for the Testbed Program was predicated on results acquired from preceding Supersonic Cruise Airplane Research (SCAR) studies and Pratt & Whitney Aircraft Advanced Supersonic Propulsion studies. These studies identified the VSCE as the most promising advanced engine concept for a future supersonic commercial aircraft. This conclusion was based on the definition and evaluation of more than 100 different engine study cycles and configurations, including conventional, unconventional and other VCE concepts.

The greater potential of the VSCE in terms of range capability, as a representative example, is depicted in Figure 4.1.2-1. As indicated, the VSCE-502B, the selected baseline study engine, offers a range advantage of approximately 7 percent over the VCE-112C concept, a rear valve configuration which showed the most promise of the various valve engines studied.

The VSCE, in terms of mechanical configuration, is similar to a conventional, twin spool turbofan engine. However, it employs variable geometry components and has a unique throttle schedule for independent control of the fan and primary exhaust streams. This independent control of flow streams, which is produced through the interaction of a low-emissions duct burner and a low-noise coannular exhaust nozzle, provides a substantial noise benefit along with improved fuel consumption.

The low-pressure spool of the engine consists of an advanced multistage, variable geometry fan and a low-pressure turbine. The high-pressure spool consists of a variable geometry compressor driven by an advanced single-stage turbine with high temperature capability.

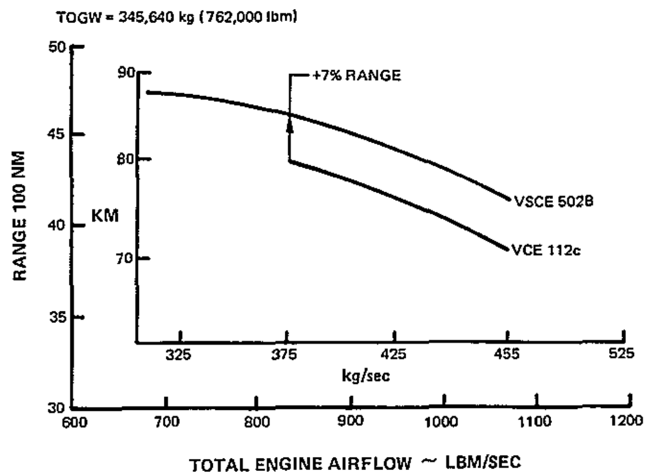

Figure 4 1 2-1 Range Comparison of VSCE-502B and VCE-112C – The data are results from the recently completed Phase IV Advanced Supersonic Propulsion System Integration Study

Both the primary combustor and the duct burner utilize low-emissions, high-efficiency combustion concepts that are particularly effective in controlling oxides of nitrogen (NO_X). The exhaust nozzle system is a coannular (concentric annular) configuration that features a variable throat area in both streams and an ejector/reverser system. Integration of the various engine and nozzle functions is managed by a full-authority, digital, electronic control system

4.1.2.2 Duct Burner Update

The definition and refinement of a duct burner design was conducted under a related NASA-sponsored technology program (contract NAS3-19781) In this program, work was directed towards the identification of two duct burner design concepts which offer the greatest potential to achieve the performance and emissions goals of the VSCE.

Using emissions and performance data acquired from the NASA/P&WA Experimental Clean Combustor Program, various duct burner concepts, ranging from conventional combustion systems to very advanced, high risk concepts, were defined and evaluated. A more comprehensive study was made of selected concepts which involved aerothermal definition, estimating performance, and an assessment of the impact on engine performance over the total mission. Refined estimates of emissions, and qualitative assessment of such factors as cost, weight, and development risk was also completed.

The results of this program led to the definition of two duct burner concepts that appeared to be compatible with the overall design goals of the VSCE-502B. The two design concepts, schematically shown in Figure 4.1 2-2, are a Vorbix (vortex burning and mixing) configuration and a premixed-prevaporized configuration The Vorbix duct burner concept was derived from the combustion technology demonstrated during the NASA/P&WA Experimental Clean Combustor Program. The second concept is a more advanced design and employs premixed combustion with external prevaporization of the fuel in a regenerative liner prior to injection into the premixing passages. Both combustor concepts utilize three axially-positioned stages of combustion: a pilot prechamber stage, a low power stage, and a high power stage During takeoff, all three stages are operative, while at supersonic cruise only the prechamber and low power stages are operative

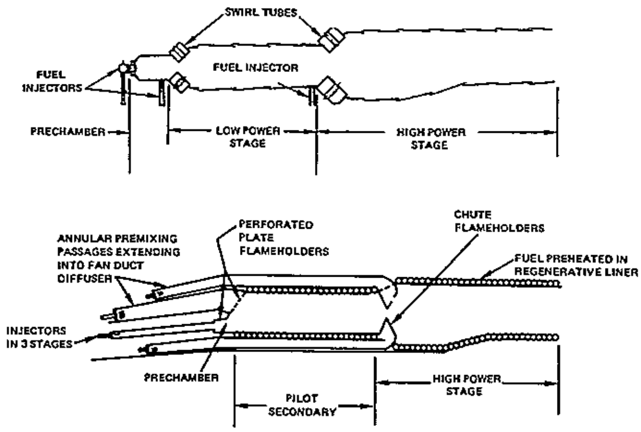

Figure 4.1.2-2 Cross-Sectional Views of the Vorbix and Premixed-Prevaporized Duct Burner Concepts - These two concepts were identified during the screening study as having the greatest potential for meeting VSCE per formance and emissions goals.

A summary of the projected emissions, performance, and pertinent physical characteristics of the two selected concepts is presented in Table 4.1.2-I. For comparison, the goals of the Duct Burner Screening Program are also tabulated. As indicated by the results, both configurations are projected to meet the chemical and thrust efficiency* goals, the total pressure loss and soft ignition requirements, and the size constraints of the VSCE-502B fan duct. The major difference between the two concepts is the projected oxide of nitrogen (NO_X) emissions level. The premixed-prevaporized system offers potentially lower NO_X emissions, particularly at the supersonic cruise condition. This advantage in emissions reduction is attained at the expense of substantial increases in system weight and development risk. A significant part of the weight increase is attributed to the regenerative fuel heating system that is unique to this concept.

***Efficiency calculation based on an effective temperature at the nozzle throat to produce thrust.**

TABLE 4.1.2-I

PROJECTED EMISSIONS, PERFORMANCE AND SIZE OF DUCT BURNERS FOR THE VSCE 502B ENGINE

	Screening Program Goal	Three Stage Premix Prevaporized	Three Stage Vorbix
Cruise Emissions			
EI NO_X	1 0	0 52	2 75
Combustion Efficiency ~%	99	99	99
SLTO Emissions			
EI NO_X	1 0	1 12	1 78
Combustion Efficiency ~%	99	99	99
Cruise Performance			
Total Pressure Loss ~%	4 5	4 25	4 25
Thrust Efficiency ~%	94 5	94 5	94 5
SLTO Performance			
Total Pressure Loss ~%	None Req'd	14 0	14 0
Thrust Efficiency ~%	None Req'd	95 5	88
Max Ignition Fuel/Air Ratio	0 002	0 002	0 002
Geometry			
Maximum Duct Height - cm (in)	33(13)	33(13)	33(13)
Length - cu (in)	168(66)	157(62)††	168(66)
Penalties			
Size	0*	None	None
Weight - Kg (lbs)	0*	740(1620†)	105(230)
Development Risk		High	Moderate

* Baseline established in previous SCAR studies
† 410 Kg (900 lbs) of penalty due to regenerative fuel heating system
†† Exclusive of premixing passages extending into fan duct diffuser

Since the requirements for high altitude NO_X emissions are not as yet established and the possibility exists for trading NO_X emissions of the duct burner and main burner at this condition, the added complexity and attendant high development risk of the premixed-prevaporized concept does not appear to be warranted. On the basis of this rationale, the three-stage Vorbix concept was selected for the VSCE study engine. Information generated during the screening study was used to update the engine layouts and projected performance of the VSCE-502B.

A schematic of the three-stage Vorbix duct burner installed in the fan duct of the VSCE-502B is shown in Figure 4.1.2-3. In addition to showing the interface of the burner with the fan duct nozzle and associated actuation hardware, the air flow requirements are listed for each combustion stage.

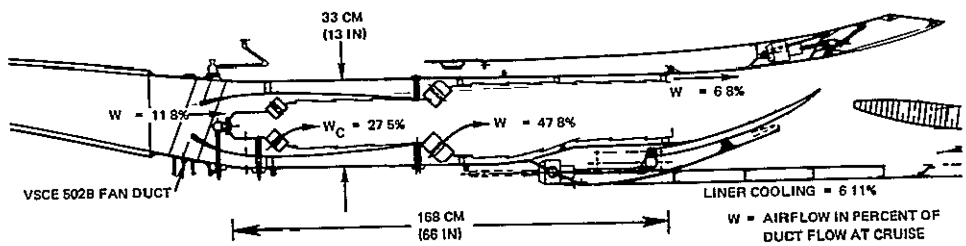

Figure 4.1.2-3 Three-Stage Vorbix Duct Burner Installed In Fan Duct - This configuration imposes a slight weight penalty that probably can be obviated through added technology development.

In the basic mechanical configuration, the pilot prechamber stage and the low power stage are enclosed by a hood to ensure a positive air management for combustion. Air enters the low power stage through a row of swirler tubes that promotes rapid mixing of air with the combustion gases existing from the prechamber stage. The rapid turbulent mixing produced by the swirling jets enhances complete combustion to reduce exhaust pollutants. A similar arrangement is also employed in the third combustion zone or high power stage. As indicated in Figure 4.1.2-3, the fuel injectors for the low and high power stages are located at the exit of the previous stage so that fuel may be rapidly vaporized in these hot combustion products. The high power stage of the duct burner, as mentioned previously, is operative during takeoff and transonic climb.

The combustor liners in both low and high power stages are a louvered design, requiring slightly more than 6 percent of the airflow for cooling.

As indicated earlier in Table 4.1.2-I, the only penalty associated with the three-stage configuration, relative to the preliminiary configurations identified during the SCAR studies, is an added increase in engine weight by 105 kg (230 lbs). This is attributed primarily to the use of a third combustion stage and the weight of an additional fuel manifold and injectors. A two-stage Vorbix duct burner, the basis for establishing the screening program goal noted in Table 4.1.2-I, was also evaluated as part of the screening program. However, it was rejected on the basis of projected difficulty in achieving the ignition fuel to air ratio, while maintaining the desired radial duct height, and because it was projected to produce slightly higher cruise NO_x emissions relative to the three-stage burner. If these anticipated difficulties can be resolved through future development, it would be possible to employ a two-stage Vorbix duct burner in subsequent generations of the VSCE-502B concept.

4.1.2.3 Coannular Nozzle Update

Under a separate NASA contract (NAS3-20061), Pratt & Whitney Aircraft has been conducting model tests of coannular nozzles. As part of this work, the coannular noise benefit associated with inverted velocity profiles has been evaluated both statically and in simulated flight. Aero/acoustic tests have been recently completed to assess the effect of radius ratio in both the core and fan streams. From these efforts, significant data have been acquired which affect the primary nozzle discharge coefficient. This information will affect the nozzle area variation required for the VSCE flight engine concept.

Aero/acoustic model tests completed to date confirm the baseline nozzle concept selected for the VSCE-502B with a nominal 0.8 radius ratio in the fan stream and a plugless configuration in the core stream. However, further evaluations, including performance substantiation, are required with this nozzle, and the additional data could change this selection.

A comparison of the VSCE flight engine concept and the VCE testbed configuration is presented in Figure 4.1.2-4. Note the similar location, in the axial direction, of the core and duct burner nozzles. Key nozzle parameters for both the core and duct streams are listed in Table 4.1.2-II for the VSCE-502B and the testbed system.

The ejector system that will be used in the testbed is a 0.52 scale size of the configuration in the VSCE-502B. Table 4.1.2-III presents a comparison of this scaling between the testbed and VSCE-502B.

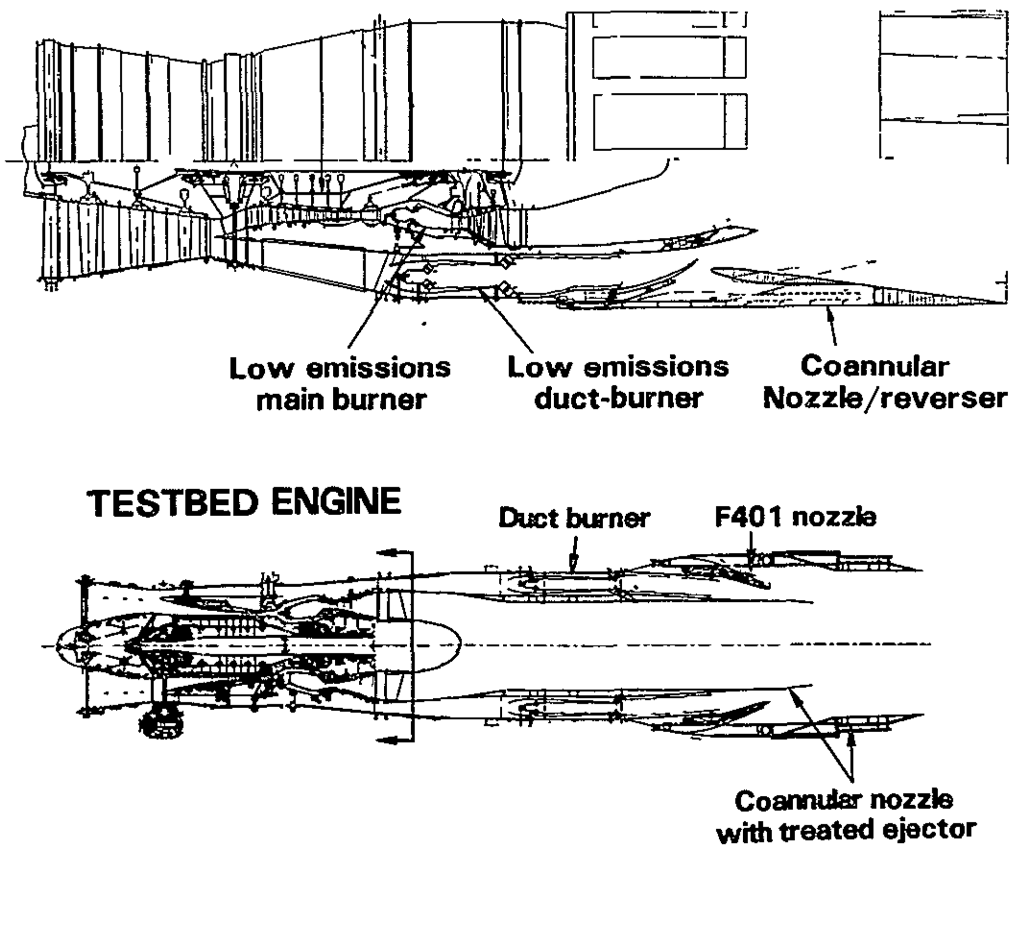

Figure 4.1.2-4 VSCE-502B and Testbed Configuration – The nozzle used in the testbed is similar to the design in the flight engine.

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TABLE 4.1.2-II

NOZZLE COMPARISON

	VSCE-502B 408 kg/sec (900 lb/sec)	VCE Testbed 105 kg/sec (232 lb/sec)
PRIMARY STREAM		
Throat Area, m^2 (In^2)	0.7169 (1110)	0.240 (373)
Pressure Ratio	1.65	1.6
DUCT STREAM (Maximum Augmentation at SLTO)		
Throat Area, m^2 (In^2)	1.103 (1710)	0.263 (406)
Pressure Ratio	2.2	2.3

TABLE 4.1.2-III

VSCE-502B AND TESTBED EJECTOR COMPARISON

	Diameter ~ m (in)	Length ~ m (in)
VSCE-502B	2.042 (80.4)	2.233 (87.9)
0.52 Scale of VSCE-502B	1.067 (42)	1.43 (45)
Testbed	1.067 (42)	1.43 (45)

- Testbed is a linear scale (LSF)* of VSCE-502B

$$*\text{LSF} = \sqrt{\frac{(A_{jp} + A_{jf})\ \text{Testbed}}{(A_{jp} + A_{jf})\ \text{VSCE-502B}}}$$

$A_{jp} \approx$ Primary nozzle area

$A_{jf} \approx$ Fan duct nozzle area

4.1.2.4 Mechanical Definition

The resulting changes in engine design imposed by refinements to the duct burner and coannular nozzle are minimal. As discussed in the preceding sections, the nozzle was confirmed as the baseline configuration for the VSCE-502B, and the duct burner design was updated to reflect an improved configuration The influence of these changes is depicted in Figure 4.1.2-5 through the overall comparison of the VSCE-502B updated configuration (bottom) with the engine definition prior to the VCE Testbed Planning and Definition Study (top).

Except for the refined Vorbix duct burner definition, the engine configuration is basically unchanged. Refinements to the duct burner, however, have not resulted in changes to the duct flow area so that the engine diameter has not changed. Similarily, the length requirement has not changed through the addition of a third combustion stage. Based on a preliminary weight analysis, there is a 2.5 percent increase in engine weight resulting from the additional hardware. This increase translates into approximately 105 kgs (230 lbs) and is due to the increase number of swirler tubes which promote higher mixing and the addition of a burner manifold and fuel nozzles for the third combustion stage.

A summary of the engine weight breakdown by major component is presented in Figure 4.1.2-6 for the baseline and updated VSCE-502B These weight changes were not used for the mission update since the design changes need to be substantiated through the design and test investigations, which were beyond the scope of work for this program. When the component modifications are finalized, a final estimated weight for the VSCE-502B can be determined

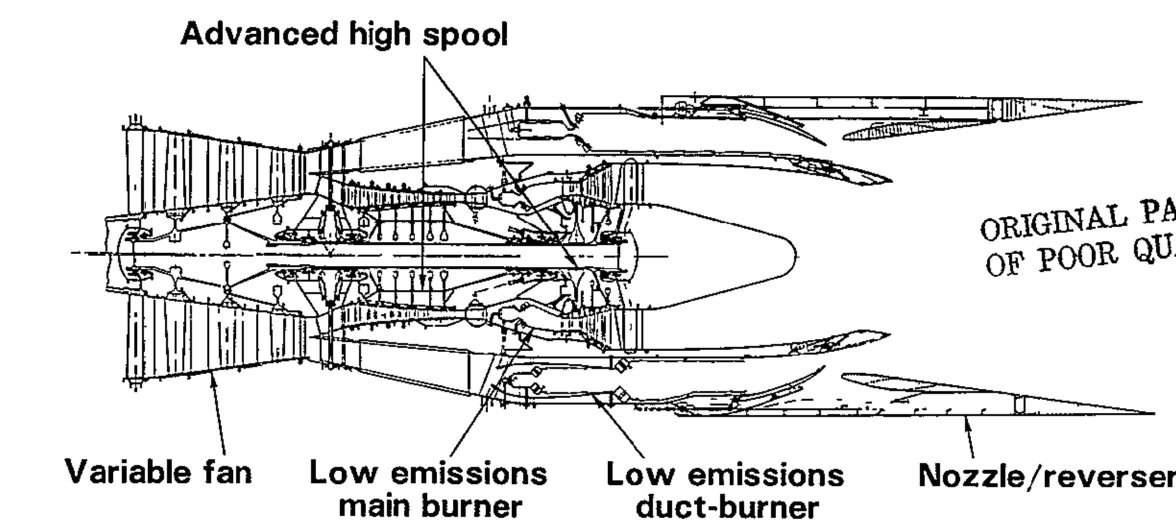

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Figure 4.1.2-5 Updated VSCE-502B Cross Section (Bottom) and Baseline VSCE-502B Cross Section (Top) at Beginning of Study - The overall engine configuration, including length and diameter, is basically unchanged.

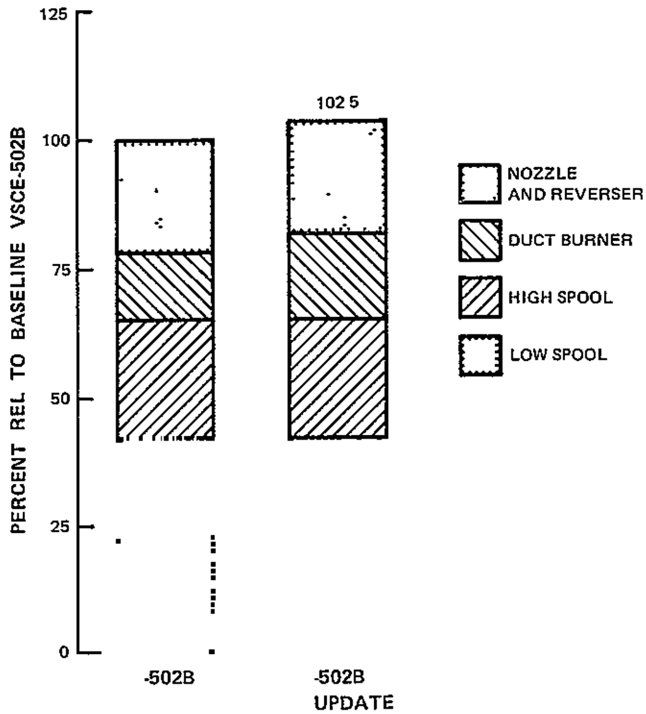

Figure 4.1.2-6 Engine Weight Breakdown - The updated VSCE-502B has a slight weight increase of 2.5 percent over the baseline definition

Engine Installation

Integrating the VSCE with the advanced, supersonic cruise vehicle concepts currently being studied by the three major airframe manufacturers does not appear to present any difficulty based on discussions with the Boeing Airplane Company, the Douglas Aircraft Company, and the Lockheed California Company. This includes conventional under wing installations of the Boeing and Douglas aircraft as well as the unique under/over wing installation in the Lockheed conceptual aircraft

Maintainability Considerations

Preliminary procedures were established for inspecting and servicing the VSCE-502B configuration. These procedures were defined by reviewing engine maintenance requirements in terms of frequent service and inspection items. Inspection requirements include items located in the pod as well as core engine locations viewed through borescopes or access panels. Overall, most of the inspection procedures conform to current practices.

4.1.3 Predicted VSCE Performance

4.1.3.1 Overall Performance and Fuel Consumption Characteristics

The performance characteristics of the updated VSCE system have remained unchanged from the baseline engine for the operating modes of climb, supersonic cruise and subsonic cruise, although a change has been made to the mode of operation during takeoff power settings. Thrust specific fuel consumption (TSFC) estimates for the VSCE-502B are shown in Figure 4.1 3-1 for both subsonic and supersonic cruise operation. For consistancy with previous performance information, the curves in Figure 4.1.3-1 are for a 408 kg/sec (900 lb/sec) engine size These trends were initially established during the Phase IV Advanced Supersonic Propulsion study completed by Pratt & Whitney Aircraft under Contract NAS3-19540 and remain unchanged at the completion of this study. Consequently, the refinements in component designs have not produced any adverse effect on fuel consumption.

The change in takeoff power settings reflects an improved method for part power operation. Previously, part power performance during takeoff was achieved by throttling the duct burner at a constant core engine match. This resulted in a reduction in the inverted nozzle velocity profile. The improved method of part power operation of the VSCE-502B during takeoff is to throttle the core engine at the same time the duct burner temperature is reduced in order to maintain a constant and optimum nozzle jet velocity ratio over a range of power settings. By means of independently varying the nozzle jet areas in the core and bypass streams, the VSCE-502B also maintains the maximum design airflow during part power takeoff conditions. This capability compliments the coannular noise benefits to enhance the overall noise characteristics of the engine. Figure 4.1.3-2 presents a comparison of the original method of scheduling the VSCE-502B during part power operation at takeoff with the present constant jet velocity ratio method.

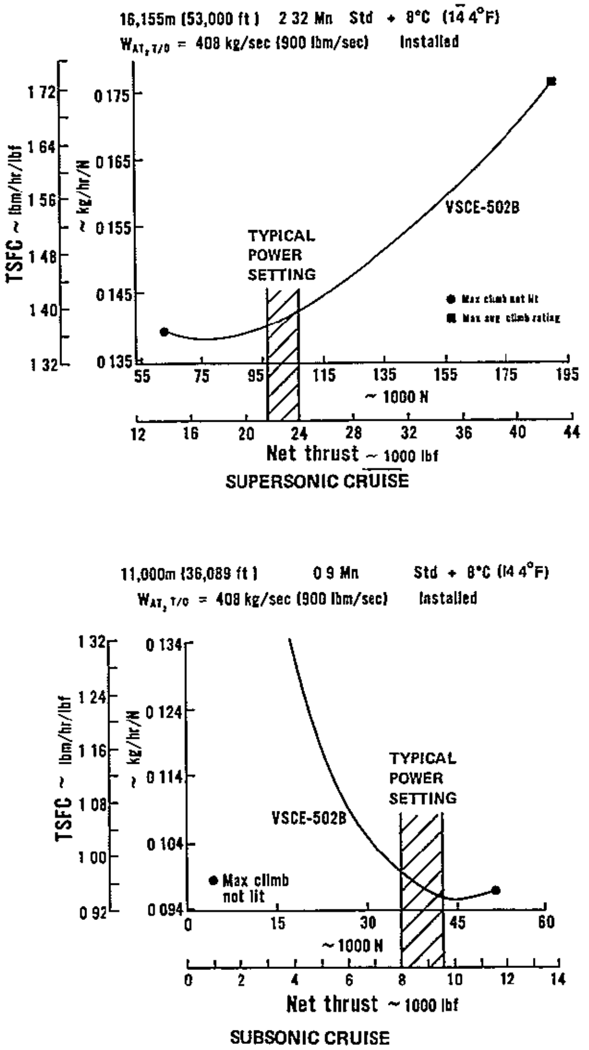

Figure 4.1.3-1 Fuel Consumption Characteristics for Supersonic and Subsonic Cruise - Updating the VSCE-502B has not produced any change in TSFC estimates for these operating conditions.

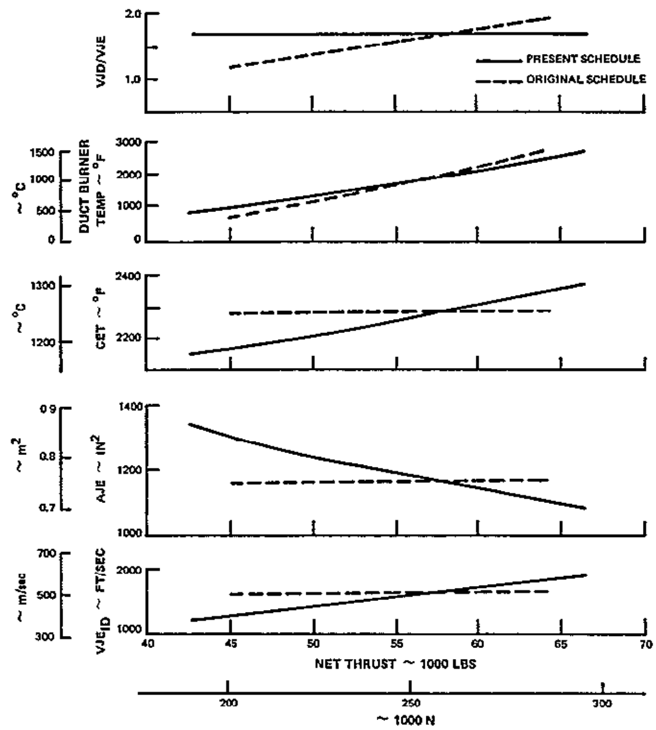

Figure 4.1.3-2 Predicted Takeoff Part Power Operation - This figure compares the original and present schedule for the VSCE-502B for improved part power performance along with enhanced overall noise characteristics

4.1.3.2 Noise Prediction Update

Engine noise levels for the VSCE-502B were calculated using a recently updated noise prediction system. The update consisted of a refinement in the procedure used to estimate engine jet noise and the addition of new procedures for evaluating turbine and duct burner combustion noise levels. The sensitivity of the VSCE fan noise to variations in inlet flow conditions and duct treatment assumptions was also examined. The noise prediction system updates are explained and the results presented in the following paragraphs.

The noise prediction system currently in use at Pratt & Whitney Aircraft consists of several modules or subroutines that have the capability to predict the noise generated by several components within the engine. The prediction of jet noise for engines with coannular inverted flow nozzles consists of two separate noise components. These noise components are low frequency merged jet, which is generated downstream of the nozzle, and high frequency premerged jet which is generated close to the nozzle exit by the high velocity fan stream. The low frequency portion is calculated by the SAE ARP 876 method, utilizing downstream merged jet properties as input. For the high frequency portion, correlations of experimental data for coannular nozzles were made in order to predict the peak sound pressure level and shape In addition, this procedure accounts for an ejector with either a hardwall or treated surface, As part of the update, the proposed SAE shock noise prediction method was added to account for shock noise created by the high velocity bypass stream. This prediction system provides an empirical method for applying test data obtained from the NASA sponsored model nozzle test program (NAS3-17866) to flight engine noise predictions.

The procedure for transforming jet noise from static to flight was updated to reflect experimental results obtained from the model nozzle jet wind tunnel flight simulation tests. Results from these tests indicate that separate relative velocity exponents exist for premerged jet noise, merged jet noise and shock noise A refined correlation between the model nozzle test data and the exhaust conditions of the VSCE was developed and included in the prediction system update.

The prediction system for fan noise has not been altered for the current update Predictions are based on a data base drawn from both engines and fan rigs, and covers ranges of key factors, including fan tip speed, stage number, and blade design.

A choked inlet noise study, sponsored by NASA (Contract NAS3-16811), was conducted at Pratt & Whitney Aircraft. Based on the results of this contract, a 20 dB inlet noise suppression was applied to account for the effect of a choked inlet. The impact of not maintaining choking flow conditions in the inlet is illustrated in the noise levels of Figure 4.1.3-3 As a result of the long fan discharge ducts in the VSCE design, a substantial amount of aft fan noise attenuation is expected. The attenuation characteristics of this treatment were estimated on the basis of test data from Pratt & Whitney Aircraft, the Federal Aviation Administration, and NASA engine and rig tests. Figure 4.1.3-3 indicates the impact of different levels of treatment on the total engine noise levels.

Engine/airframe integration studies are being conducted in parallel with the Testbed Program (final reports not yet released). From these studies, a representative size for the VSCE-502B for the FAR Part 36 noise level is 340 kg/sec (750 lb/sec). Therefore, the noise prediction update discussed here is for this engine size, and not the 408 kg/sec (900 lb/sec) size that performance data are based on.

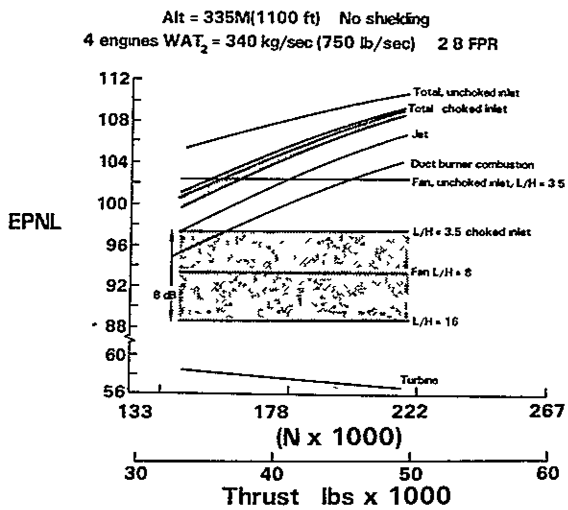

Figure 4 1.3-3 VSCE-502B Sideline Noise Update – As shown, turbine noise is insignificant, fan noise has a slight effect on total noise, depending on the level of acoustic treatment (L/H) in the duct behind the fan, and combustion noise from the duct burner may have a small effect on total noise.

A main burner combustion noise prediction system was the result of an FAA sponsored test and analytical program This prediction system is not intended for VSCE cycles, and extrapolating it to duct burner conditions is questionable Some preliminary predictions for duct burner combustion noise were made using this approach and the results are included in the total VSCE-502B noise estimates. The inclusion of duct burner noise is part of the prediction system update.

Results from a revised turbine noise prediction procedure were also included. Levels of turbine noise are relatively low for the VSCE configurations at takeoff, cutback and sideline, and do not contribute to the total noise. At approach, this noise source may become significant.

The noise estimates for the VSCE-502B are summarized in Figure 4 1 3-4. The range of values represents the possible variations in engine operating procedure and assumptions regarding various noise treatment geometries.

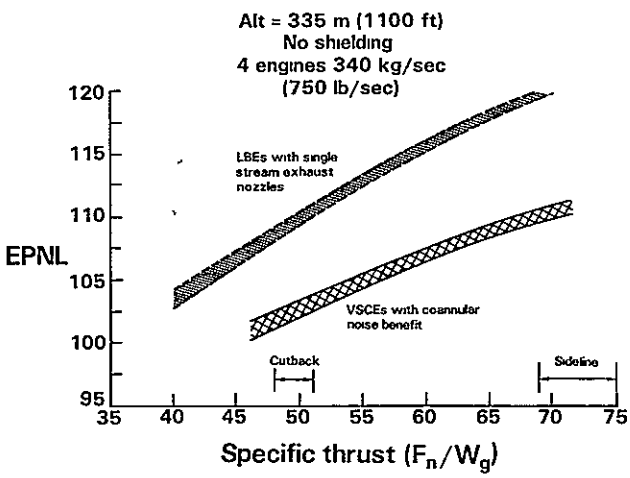

Figure 4.1.3-4 Sideline Noise Estimates – VSCE concepts with the coannular noise benefit are compared with different configurations of a Low Bypass Engine (LBE)

The VSCE-502B levels are compared with a family of conventional unsuppressed single stream nozzles.

4.1.3.3 Exhaust Emissions Prediction Update

The projected emissions characteristics of the VSCE-502B were updated to reflect improvements in the emissions data base acquired from two main sources. These included the results from the NASA/P&WA Experimental Clean Combustor Program and the NASA-sponsored duct burner screening study under contract NAS3-19781

Recently, the test results from the engine evaluation of the Vorbix combustor under Phase III of the Experimental Clean Combustor Program became available. The data were used for projecting the emissions of the main combustor in the VSCE-502B. Also, the results of the duct burner screening study have provided a more comprehensive definition of the duct burner and its emissions characteristics than achieved under preceding SCAR definition studies

With assimilation of this information into the existing data base, revised estimates were computed of VSCE-502B exhaust emissions. Figure 4 1 3-5 shows the projected emissions levels for both airport vicinity and altitude cruise as a function of chemical combustion efficiency of the duct burner. The shaded area depicts emissions from the main combustor, while the unshaded area depicts the emissions from the duct burner. The projections of the different pollutants are based on direct scaling of the new data, and do not reflect any allowance for deviation from a nominal engine deterioration or additional development of the combustors.

The results indicate that by incorporating the technology demonstrated in the Experimental Clean Combustor Program in both the main

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combustor and the duct burner the engine is capable of meeting the 1984 airport vicinity NO_x emissions requirements for Class T5 engines. However, when the duct burner is designed for 99 percent combustion efficiency (the goal of screening study of NAS3-19781), carbon monoxide (CO) pollutants are nearly twice and the unburned hydrocarbons (THC) 50 percent above the Environmental Protection Agency Parameter (EPAP) required levels. The excessive CO and THC emissions are attributable to duct burner operation at takeoff and climbout To reduce the overall output of these pollutants to the required airport vicinity levels, it is necessary to increase the chemical combustion efficiency of the duct burner from 99 percent to 99.6 percent. The cruise NO_x could be reduced by a reduction in cycle overall pressure ratio below the design value of 20 This reduction would not affect supersonic performance but would compromise subsonic cruise TSFC.

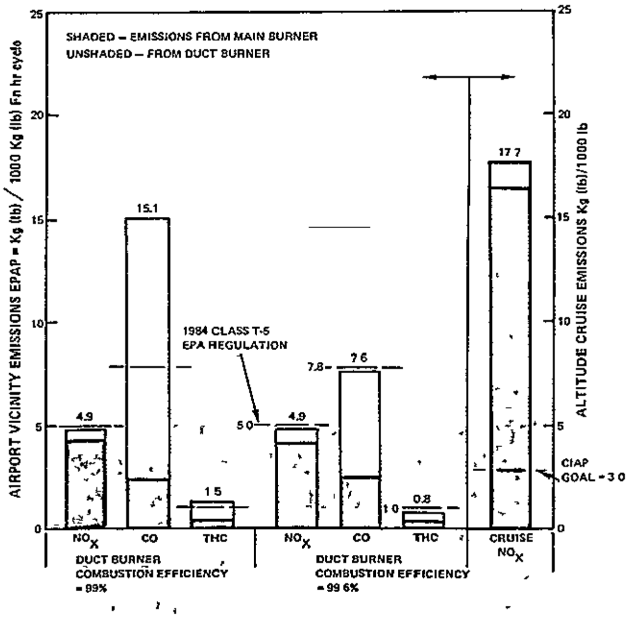


Figure 4 1.3-5 Updated VSCE-502B Emissions Estimates - A chemical combustion efficiency of 99.6 percent is required to meet the 1984 Environmental Protection Agency CO rule for advanced supersonic engines

The NO_x emissions at high altitude cruise, as indicated in Figure 4.1.3-5, are substantially higher than the proposed Climatic Impact Assessment Program (CIAP) goal of 3.0. Although the requirements for altitude NO_x are not as yet established, if they are constrained to this proposed level, more advanced emissions-reduction technology must be employed in gas-turbine engine combustors to meet the goal. Since the main combustor produces nearly 90 percent of the NO_x emissions at the supersonic cruise condition, it would be advantageous to introduce new emissions-reduction technology to the main combustor with a priority higher than the duct burner. The duct burner, however, could also utilize this new technology to lower emissions.

4.1.4 Engine Sizing and Mission Results

Mission analyses of the VSCE-502B were conducted using the same ground rules and procedures as in Phases II, III and IV of the Advanced Supersonic Propulsion study (Contract NAS3-19540). As a summary, the mission analysis ground rules are presented in Table 4.1.4-I as well as the following paragraphs However, a complete description is presented in the Advanced Supersonic Propulsion Study Phase II Final Report (NASA CR-134904)

TABLE 4.1.4-I

MISSION ANALYSIS GROUND RULES

Airplane Design	Modified Arrow Wing (NASA CR-13-2374)
Flight Mach Number	2.4
Thrust Loading	Base 0.275, Alternates 0.24 and 0.32
Payload	292 Passengers
Takeoff Gross Weight (TOGW)	345640 Kg (762000 lbm)

TABLE 4 1.4-1 (Cont'd)

Range	Variable	
Fuel Reserves	As Defined in Lockheed Report LR-26133	
Inlet	Axisymmetric Mixed Compression	
Design Missions	Nominal	All Supersonic
	Alternate	Mixed with 1110 Km (600 nautical miles) Initial Subsonic Cruise

For this analysis, the airplane aerodynamics from NASA CR-132374 were modified to account for pod drag differences caused by engine size variations Airplane empty weight included the effects of engine size on engine and pod weight Climb power settings (duct burner augmentation levels) were optimized to maximize overall mission range

Engine corrected airflow divided by airplane takeoff gross weight (WAT_2/TOGW) is used as the engine size parameter in advanced supersonic technology mission evaluations because the range capability of the airplane is essentially a unique function of this parameter for a given engine type. The takeoff field length capability is related to the airplane thrust loading, 4 (Fn)/TOGW, for a four-engine airplane. The higher the thrust loading the shorter the takeoff field length Both Fn/TOGW and WAT_2/TOGW are defined at 370 km/hr (200 kts) at sea level on a standard +10°C day Theoretical jet noise of an engine is directly related to its specific thrust (Fn/WAT_2), which can be calculated from the following equations

$$Fn/WAT_2 = \frac{4\,(Fn)\ TOGW}{4\,(WAT_2)\ TOGW}$$

Since airplane range is a function of WAT_2/TOGW and engine noise is a function of Fn/WAT_2, this equation can be used to relate noise for any given aircraft takeoff thrust loading for a specific engine type, providing that appropriate distance, shielding and inverted velocity effects are included

The parameter WAT_2/TOGW is a good one mainly because jet noise can be related to it in a gross way at a fixed Fn/TOGW, if the V_{jd}/V_{jc} is constant Range is not a unique function of WAT_2/TOGW, however. For example, TOGW can be reduced at constant WAT_2/TOGW until range = 0 because fuel weight equals 0 Range is a unique function of WAT_2 for a given airplane with fixed TOGW

Figure 4 1 4-1 shows the VSCE-502B engine size-airplane range relationship for the nominal (all supersonic) and mixed missions Since the VSCE-502B baseline performance has not changed from the estimates defined in the Phase III Advanced Supersonic Propulsion study the trends shown in this figure have not changed. However, noise estimates for the VSCE-502B with the inverted velocity profile have changed. A minimum change in these results would occur for the added weight from the three stage vorbix duct burner (Δ=24 n. mi.). However, noise estimates for the VSCE-502B with the inverted velocity profile have changed As a result, the noise effect on airplane range is different in comparison to that identified in the Phase III study The updated noise levels are shown in Figure 4.1.4-2 along with the Phase III noise levels. The primary reason for the noise difference is the inclusion of new flight effects data in the Pratt & Whitney Aircraft noise prediction system

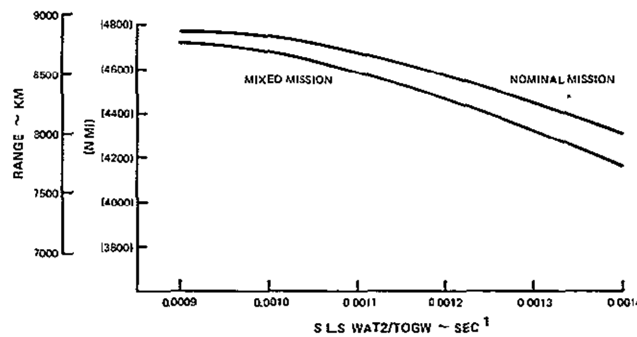


Figure 4 1 4-1 VSCE-502B Engine Size and Range Relationship - These trends have not changed from earlier Phase III studies since VSCE-502B performance has not changed

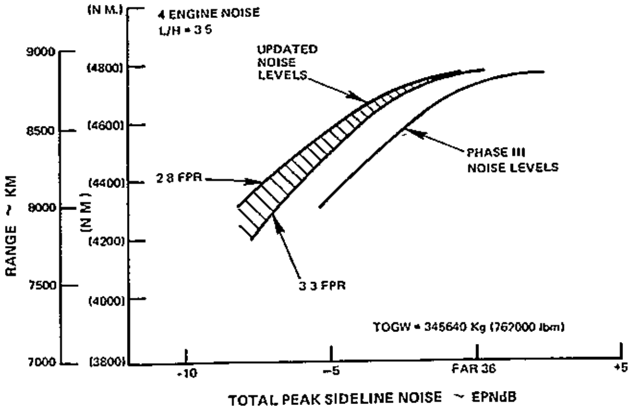


Figure 4 1 4-2 Effect of Updated Noise Levels - Effect of revised noise estimates on mission range is less that 1 percent at FAR-36 noise level, increasing to 4-5 percent at FAR-36-5dB

The band shown for the revised noise levels in Figure 4 1 4-2 represents the difference between operating at the engine nominal fan pressure ratio (FPR) of 3 3 (higher noise side of the band) at takeoff versus operating at a fan pressure ratio of 2.8 (lower noise level). Operating at the lower pressure ratio requires more augmentation to attain a specified thrust level in contrast to the higher pressure ratio. Consequently, if combustion noise from the duct burner is eventually determined to be a problem, the noise levels estimated with the lower fan pressure ratio system may not be achievable

Figures 4.1.4-3 and 4 1 4-4 present summaries of mission range capabilities at various revised peak sideline noise levels for takeoff thrust to weight ratios of 0 24, 0 275, and 0 32 The range estimates using the revised noise levels for the nominal mission are presented in Figure 4.1.4-3, and Figure 4.1.4-4 presents the same information for the mixed mission. The FAR-36 reference point in each figure corresponds to an effective perceived noise level (EPNL) of 108 decibels.

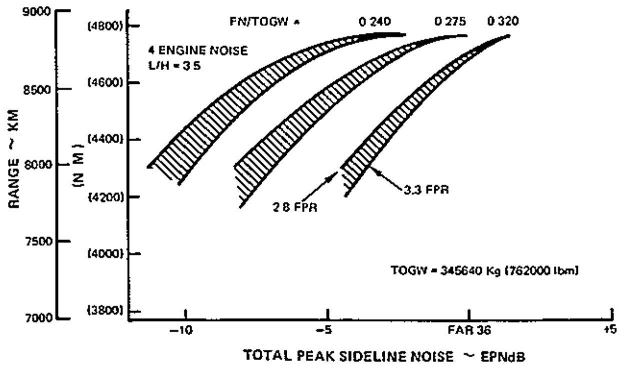


Figure 4 1 4-3 Range Capability for Nominal Mission - Revised mission range trends at various peak sideline noise levels are shown for different thrust to weight ratios

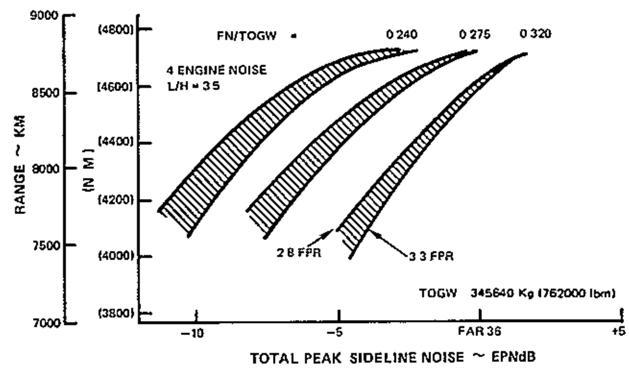


Figure 4.1 4-4 Range Capability for Mixed Mission - Revised mission range trends at various peak sideline noise levels are shown for different thrust to weight ratios

4.1.5 Technology Sensitivity Study

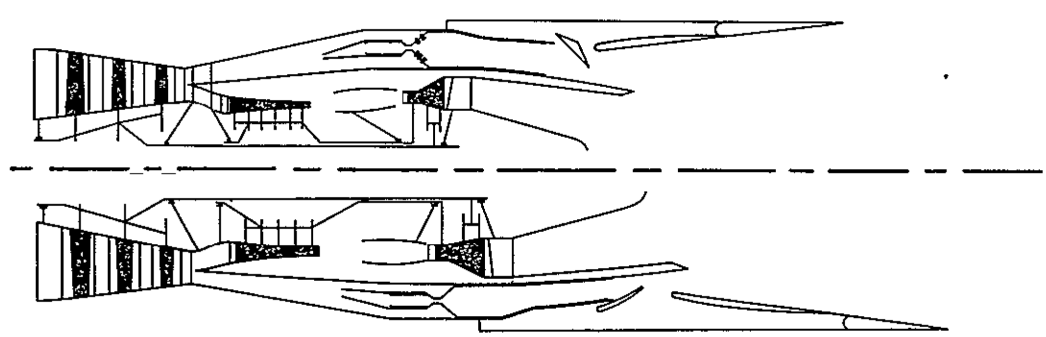
A study was conducted to determine the performance differences between a VSCE using near-term technology as opposed to the far-term technology used in the definition of the VSCE-502B. The assessment of technology difference was made by comparing a VSCE derivative, designated VSCE-511, which has a technology readiness in the early 1980 time period, with the VSCE-502B, a late 1980 engine. This amounts to a five year difference in technology readiness level between the two engine concepts.

4.1.5.1 Near-Term Technology Engine Definition

The VSCE-511 concept was derived from the VSCE-502B by adjusting cycle temperatures and pressures to meet the technology limits for the nearer term period. The mechanical configuration of the VSCE-511 concept is essentially the same as the 502B, with added weight and length resulting from cycle changes. Figure 4.1.5-1 shows a comparison of the engines.

The thermodynamic cycle of the VSCE-511 was defined by using the same fan pressure ratio (3.3) and main combustor throttle ratio (1.195) as the VSCE-502B. (Main combustor throttle ratio is defined as the combustor exit temperature at the maximum climb level divided by the combustor exit temperature at takeoff.) As a result of decreased cycle temperatures and increased cooling air the bypass ratio of the VSCE-511 was lowered to maintain the same nonaugmented exhaust velocity ratio as the 502B (V_{J_D}/V_{J_E} = 1.0) at the sea level static takeoff turbine temperature. The cycle overall pressure ratio was lowered to maintain a maximum compressor discharge temperature of 620°C (1150°F) at the supersonic cruise flight condition, compared to the VSCE-502B discharge temperature level of 705°C (1300°F) at the same condition.

VSCE-502B



VSCE-511

Engine	-502B	-511
Dimensions m (in)		
D_{max}	2 24 (88)	2.24 (88)
L_{total}	6 76 (266)	7.26 (286) (+7 5%)
Weights kg (lbm)		
BEW	4765 (10,500)	5445 (12,000)
Eng. + N/R	6080 (13,400)	6985 (15,400) (+15%)
airflow size		
408 kg/sec (900 lb/sec)		

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Figure 4.1.5-1 Engine Comparison - The major differences between the two engine concepts are in the hot section components and exhaust nozzle configuration.

4.1.5.2 Performance Trends

The areas of principal interest in assessing technology sensitivity are the hot section components in the engine. The burner liner materials projected for the near-term VSCE have a lower metal temperature capability which introduces required cycle changes. The effect of this on the main combustor is to limit the maximum compressor discharge temperature by lowering the cycle overall pressure ratio. For the duct burner, an increase in cooling air is required. This additional cooling flow increases the bypass stream losses, thereby reducing engine performance at each augmented flight condition. Since the VSCE operates with duct burning augmentation at the supersonic cruise flight condition, the impact of these losses becomes significant.

Turbine materials, including airfoil and disk materials, are also affected by the lower temperature capability. Lowering the cycle overall pressure helps in cooling the turbine disks and airfoils, but reduced combustor exit temperatures and increased cooling flows are still necessary to maintain commercial durability and life requirements These changes necessitate a decrease in bypass ratio to maintain the optimum jet velocity ratio between the primary and fan duct streams. This velocity ratio is important in establishing takeoff noise levels, and to maximize performance at subsonic and supersonic cruise operating conditions.

In addition to lowering the turbine airfoil metal temperatures, the blade root stress levels must be decreased. Lower stresses are obtained by reducing the design rotor speed, which in turn, necessitates compressor flowpath changes such as increased diameter of additional stages to limit the design loading levels. Such changes in the engine configuration serve to increase the overall engine weight.

The effect of technology level on VSCE performance is shown by the mission performance characteristics listed in Table 4.1.5-I. In this table, the cycles of the two study engines are listed along with the VCE testbed engine cycle. Since the testbed cycle is close to either the near or far-term engine, the VCE component and testbed programs will provide nozzle and duct burner design information and data that are applicable to both levels of technology readiness.

TABLE 4.1.5-I

EFFECT OF TECHNOLOGY ON VSCE PERFORMANCE

Cycle Characteristics	VSCE-511	VSCE-502B	VCE Testbed
FPR	3 3	3.3	3.1
CET °C (°F)	1370 (2500)	1480 (2700)	1200 (2200)
TCA (%)	15	11	--
BPR	0 85	1.3	0.9
CDT_{MAX} °C (°F)	620 (1150)	705 (1300)	--
OPR	13 4	20	21
Mission Performance			
Supersonic TSFC (%)	+1 7	Base	--
Subsonic TSFC (%)	+8.0	Base	--
Engine Weight (%)	+15 0	Base	--
Range (%)	-7 0	Base	--

From a cycle standpoint, the five year difference in technology is most apparent in the lower percentage of turbine cooling air (TCA) and the increase in combustor exit temperature for the VSCE-502B However, the application of near-term technology also has an adverse effect on engine performance, fuel consumption, weight and mission range. The effect on aircraft range is a decrease of 7 percent for the VSCE-511 engine relative to the VSCE-502B

A series of technology trends is presented in Figure 4.1.5-2 to further illustrate the cycle and performance improvements that are achievable through the application of far-term technology advances These trends compliment the mission performance results presented in Table 4 1 5-I.

4.2 VCE TESTBED DESIGN DEFINITION

4.2.1 Introduction

Work in this part of the program was directed at establishing the preliminary design definition of the VCE testbed configuration for testing the two critical components the low-emissions duct burner and the low-noise coannular nozzle Under related NASA technology programs, the feasibility of these components has been demonstrated during small-scale testing However, for verification of this technology, large-scale testing of these components in a representative engine operating environment is required. This verification testing is planned for the next phase of the overall VCE Testbed Program. In addition, this large-scale engine test may serve to identify other areas

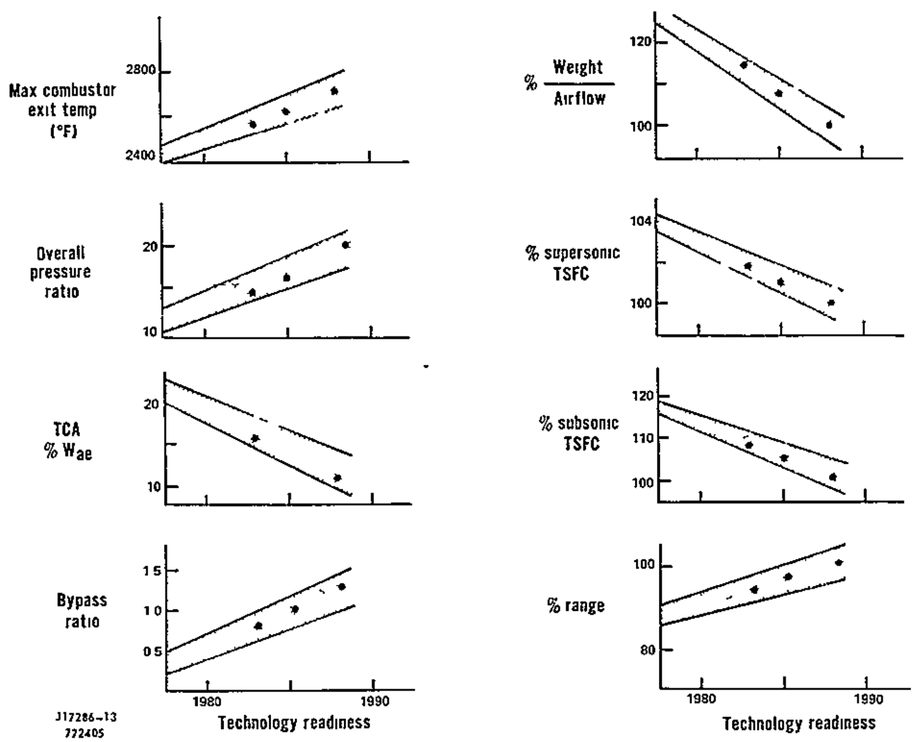

Figure 4 1.5-2 VSCE Technology Trends - Benefits in cycle operating characteristics and overall system performance are clearly apparent through the utilization of far-term technical advances.

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requiring technology improvement to ensure the establishment of a viable technology base for second generation supersonic transport engines.

The objectives of the overall VCE Testbed Program are listed in Table 4.2 1-I. The technical approach outlined for the Testbed Planning and Definition Study to meet these overall program objectives consisted of the following:

- Establish testbed design criteria
- Select core engine
- Define conceptual mechanical configuration
- Define control system requirements
- Define instrumentation requirements
- Select test facilities

TABLE 4.2.1-I

VCE TESTBED PROGRAM OBJECTIVES

DEMONSTRATE:

- Coannular noise benefit
- Low-emissions duct burner
- High levels of duct burner performance
- Acoustic treatment effectiveness
- VSCE cycle characteristics - inverse throttle schedule

EVALUATE:

- Duct burner combustion noise
- Fan/duct burner noise interactions
- Fan/duct burner/nozzle stability
- Core noise source
- Validity of noise prediction based on model test data
- Improvements to AST jet noise prediction

4.2.2 Testbed Design

The VCE testbed system, as a technology demonstration vehicle, will be designed to conform with current Pratt & Whitney Aircraft rig hardware standards. These design standards are intended to ensure complete demonstration of aerothermodynamic concepts. A demonstration of the structural life requirements of potential advanced technology supersonic engines is beyond the scope of this program, but will be a necessary follow-on to this program.

4.2.2.1 General Design Criteria

For the mechanical design of the testbed system, general design criteria must be established for areas of concern Also, operating limits and experimental data verification requirements must be established. The specific areas to be considered in defining the testbed design criteria include: engine and rig interface definition, operating requirements and limits; structural-mechanical, aerodynamic and thermal limits, duct burner, nozzle and ejector designs, range of test parameters, instrumentation and control requirements.

The design criteria should be established early in the design phase of the program and will supersede or extend Pratt & Whitney Aircraft normal design practices or F100 engine design criteria as well as be consistent with NASA requirements. Criteria for all loads, life design margins and requirements will be defined. The testbed engine operating characteristics and performance, operating limits from mechanical, thermal, and aerodynamic standpoints will be established for the F100 engine and the associated duct burner and exhaust nozzle test hardware. This will include mounting arrangements and interface definitions, in addition to maximum load conditions, structural life requirements, allowable stresses, stability limits, materials, and safety requirements.

The range of test parameters to acquire meaningful noise (with and without acoustical treatment for the ejector) and emissions data will be used to define overall performance parameters (airflows, pressures, temperatures) and *"health"* monitoring parameters (metal temperatures, stresses). Finally, control and instrumentation requirements will be established for the F100 engine testbed This definition will encompass structural considerations and consider the accuracy of test data to be obtained during the program.

4.2.2.2 Core Engine Selection

Three Pratt & Whitney Aircraft production engines were considered and evaluated as the core engine for the VCE testbed system. The candidate engines considered were the TF30, TF33, and the F100-PW-100. These engines encompass a range of total airflow sizes, fan pressure ratios and bypass ratios, and each engine is capable of being modified to accept the low-emissions duct burner and the low-noise coannular nozzle A brief description of the mechanical configuration of each engine is presented in the following paragraphs.

The TF30-P-1 engine is an axial-flow turbofan with a moderately high bypass ratio and compression ratio. The basic engine configuration, as shown in Figure 4 2.2-1, consists of a low-pressure spool with a three-stage fan, six-stage low-pressure compressor, and a three-stage low-pressure turbine. The high-pressure spool consists of a seven-stage compressor unit and a single stage high-pressure turbine. The combustion system consists of eight can-annular chambers. Different models of the engine are equipped with an afterburning system having a fully modulating, flap-type convergent primary nozzle and a blow-in-door ejector with variable inlet and exhaust areas.

The TF33 engine is also an axial-flow, twin-spool turbofan. The low-pressure spool in the TF33 engine is comprised of a two-stage fan, seven-stage low-pressure compressor unit, and a three-stage turbine system. The high-pressure spool consists of a seven-stage compressor that is driven by a single-stage high-pressure turbine. The combustor is a can-annular configuration. A cross-sectional view of the TF33 engine is presented in Figure 4.2.2-2.

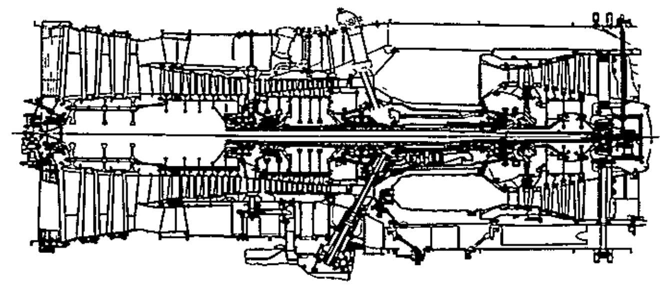

Figure 4 2.2-1 TF30 Engine Cross Section - Derivatives of the basic TF30 engine are used in such Military applications as the F-111 and A-7 fighter aircraft.

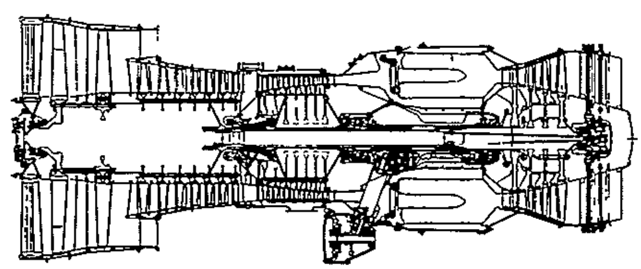

Figure 4 2.2-2 TF33 Engine Cross Section - Derivatives of the basic TF33 engine power models of the B-52 long range bomber and the C-141 cargo aircraft.

Of the three engines considered for the testbed, the F100-PW-100 is the more advanced in terms of technology level. As shown in Figure 4.2.2-3, the F100-PW-100 is a twin-spool turbofan with mixed-flow augmentation. The fan is a three-stage system that is driven by a two-stage low-pressure turbine. The compressor in the high-pressure spool is a ten-stage system that is driven by two air-cooled turbine stages. The inlet vanes to the high-pressure compressor have variable geometry capability along with the first two stator rows. Unlike the other engines, the F100-PW-100 has an annular combustor design. The mixed-flow augmentor utilizes circumferential pilot-burners and radial "V-gutter" flameholders. The exhaust nozzle is a balanced beam configuration, which provides a light weight, compact design

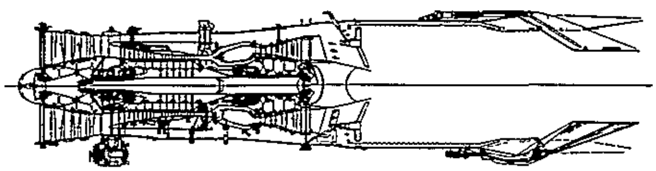

Figure 4 2.2-3 F100-PW-100 Engine Cross Section - This engine is the powerplant for the advanced F-16 weapon system, and incorporates numerous technology advances.

The cycle characteristics of the three candidate engines are presented in Table 4.2.2-I along with the VSCE-502B for comparison. Overall, the F100-PW-100 engine most closely duplicates the VSCE-502B cycle characteristics, particularly, bypass stream conditions. On the basis of this similarity and other factors as noted below, the F100-PW-100 engine was recommended and selected for the testbed.

Although the TF30 and TF33 engines closely match the VSCE bypass ratio, the limited combustor exit temperature capability and low fan pressure ratio of these engines does not provide enough flexibility when rematched to the VSCE-502B cycle conditions. Consequently, these engines are not capable of providing the proper duct burner inlet conditions and the attendant flexibility to fully evaluate the coannular noise benefit.

TABLE 4.2.2-I
CANDIDATE ENGINE CYCLE CHARACTERISTICS ALONG WITH VSCE-502B

	VSCE-502B	F100-PW-100	TF30	TF33
Total corrected	272 - 408	125	104	230
airflow ~ kg/sec (lb/sec)	(600 - 900)	(227)	(230)	(508)
Bypass ratio	1.3	0.63	0.9	1.26
Fan pressure ratio	3.3 (2 8)	3.1	2.1	1.9
Overall pressure ratio	20	25	16.5	15.6
Combustor exit	1482	1404	982	926
temperature ~°C (°F)	(2700)	(2560)	(1800)	(1700)
Bypass stream conditions				
at fan exit plane				
Pressure ~ N/m^2 (psia)	41.5 (33)	42	28	26
Temperature ~°C (°F)	153 [144]	148	136	80
	(302 [292])	(300)	(207)	(177)
Primary stream conditions				
at turbine exit plane				
Pressure ~N/m^2 (psia)	1.86×10^5 1.72×10^5	$3\ 03 \times 10^5$	2.06×10^5	1.93×10^5
	(27 [25])	(44)	(30)	(28)
Temperature ~°C (°F)	637 [671]	746	521	478
	(1180 [1240])	(1376)	(970)	(894)

In contrast, the F100-PW-100 engine, because of the high fan pressure ratio and combustor exit temperature capability, has the potential to be rematched to duplicate the inverted velocity profile associated with the coannular noise benefit. By removing the mixed-flow afterburner system and single-stream nozzle and replacing these components with the VCE duct burner and separated-stream coannular nozzle, the F100-PW-100 engine has the potential to approximate the desired exhaust conditions of the VSCE-502B. In addition, the rematched F100 also has the potential to simulate the exhaust condition of the VSCE-511, the near-term technology concept, as indicated in Table 4.2.2-II.

4.2.2.3 Predicted Performance

Performance predictions of the VCE testbed system were made by integrating the performance simulation of a F100 engine with the VCE testbed simulation. A baseline simulation of a representative F100 was obtained from the Pratt & Whitney Aircraft Group Government Products Division. The F100 simulation was converted to the VCE testbed by analytically removing the afterburner and common nozzle routines, and incorporating separate nozzles for the core and bypass streams. Also, a duct burner routine was added to the bypass stream. The appropriate pressure losses associated with the duct burner and bypass flow duct were incorporated into the simulation.

TABLE 4.2.2-II
COMPARISON OF REMATCHED F100 WITH VSCE-502B AND VSCE-511 CYCLES

Cycle	Far-Term VSCE-502B	Nearer-Term VSCE-511	Testbed (rematched F100)
Fan pressure ratio (design level)	3.3	3.3	3.1
Overall pressure ratio	20	13.4	20.8
Bypass ratio	1.3	0.85	0.91
Max combustor exit temp ~ °C (°F)	1204 (2200)	1093 (2000)	1204 (2200)
Fan pressure ratio	2.8 - 3.3	2.8 - 3.3	3.1
Exhaust condition			
Velocity ratio (duct/engine)	1.7	1.7	1.7
Nozzle area ratio (duct/engine)	1.0 - 1.4	0.7 - 1.1	0.79
Airflow ratio (duct/engine)	1.3 - 1.5	0.8 - 1.1	0.93
Duct burner condition			
Inlet temp °C (°F)	143 - 153 (290 - 310)	143 - 153 (290 - 310)	152 (307)
Exit temp °C(°F)	1148 - 1287 (2100 - 2350)	1287 - 1426 (2350 - 2600)	1165 (2130)
Pressure N/m^2 (psia)	2.27×10^5 2.89×10^5 (33 - 42)	2.2×10^5 2.89×10^5 (32 - 42)	2.44×10^5 (35.5)
Fuel/air ratio	0.03 - 0.035	0.036 - 0.042	0.031
Net thrust ~ kgs (lbs)/total corrected airflow kgs/sec (lbs/sec)	66 - 69	66 - 68	63.5

With the requirement to open the primary nozzle to achieve jet velocity variations, an accurate representation of the turbine exit guide vane pressure loss characteristics was necessary. Although the Pratt & Whitney Aircraft Government Products Division furnished guidelines on the relation of primary nozzle areas and turbine exit guide vane pressure losses, a pressure loss profile was not available which covered the range of operation required for the testbed. However, it was determined that the information supplied by the Government Products Division could be matched very closely with the use of a JT9D turbine exit guide vane swirl map for the testbed operating range. Therefore, a swirl module with this profile was integrated into the testbed simulation to complete the construction of the F100 testbed simulation.

In the testbed, the maximum fan jet velocity is determined by the duct burner maximum average temperature of 1430°C (2600°F). In order to achieve the desired nozzle jet velocity ratio in the testbed of approximately 1.8 to 2.0, the core jet velocity must be limited to about 450 m/sec (1500 ft/sec), which is considerably lower than that of the F100 at maximum power. To achieve the required primary jet velocity, the F100 is operated at lower combustor exit temperatures. The primary nozzle jet area is increased to maintain the design total airflow at the lower combustor exit temperature. With the testbed simulation, predictions of performance and component operating conditions were established for design point operation as well as other critical operating points that were selected on the basis of the testbed program requirements. The predicted performance is shown in Table 4.2.2-III with the comparison of the base F100 match to the match of the F100 in the testbed for the design point and two critical operating points. For each F100 match point for the testbed, the predicted performance included duct burner operation from not lit to maximum augmentation conditions. This information was used to establish an aerothermal definition of the flowpath in the testbed engine, the first step in the mechanical design process.

TABLE 4.2.2-III

PREDICTED TESTBED PERFORMANCE

	F100 Base	Design Point	Testbed Primary Nozzle Area 1	Testbed Primary Nozzle Area 2
Total Airflow ~ kg/sec (lbs/sec)	103 (227)	105.4 (232.5)	99.3 (219)	90.2 (199)
Fan Pressure Ratio	3.1	3.12	2.93	2.63
CET ~ °C (°F)	1406 (2563)	1208 (2206)	1146 (2095)	1062 (1943)
Duct Burner Temp ~ °C (°F)	N.L.	1427 (2600)	1427 (2600)	1427 (2600)
Duct Jet Area ~ m^2 (in^2)	0.077 (119*)	0.241 (373)	0.241 (373)	0.241 (373)
Primary Jet Area ~ $in.^2$ m^2 (in^2)	0.177 (275*)	0.262 (406)	0.245 (380)	0.226 (350)
Primary Jet Velocity ~ m/sec (ft/sec)	734.6 (2410)	454.4 (1491)	441.0 (1447)	413.3 (1356)
Jet Velocity Ratio	--	1.9	1.9	1.9
Jet Velocity Ratio (D.B. not lit)	--	0.98	0.97	0.96

*Choked flow area simulation of common flow shown as separate streams.

The operation of the F100 in the testbed configuration does not impart any changes to the operating characteristics of the F100 high-pressure spool The high-pressure compressor operates on its normal operating line However, the fan operates on a slightly different operating line in relation to the base F100 mainly because of the difference in scheduling the testbed nozzle areas relative to the jet nozzle in the base F100 engine.

In Figure 4.2.2-4, the predicted fan characteristics of the testbed are compared to the base F100 As indicated, the overall operating characteristics are very similar.

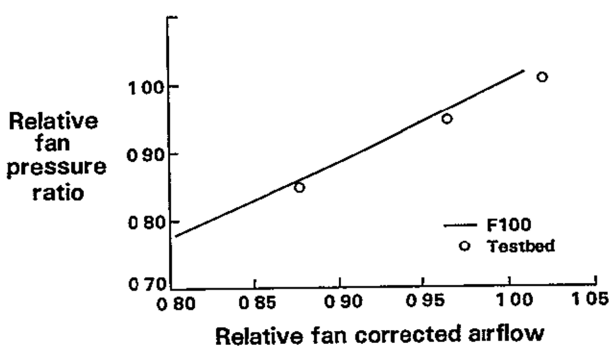

Figure 4 2 2-4 Testbed Fan Characteristics – In comparison to the base F100 engine the fan in the testbed operates on a slightly lower operating line

In addition to establishing the baseline performance predictions, operating limits were defined for the testbed system. Testbed operation must be controlled such that mechanical, aerodynamic, and thermal operating limits are observed for the F100 core engine as well as the duct burner When compared to the F100 mixed-flow, afterburning configuration, the testbed operates at reduced turbine temperatures and high-pressure rotor speeds and increased low-pressure rotor speeds to achieve the design fan duct airflow and pressure ratio. The F100 gas generator operating limits are based on the "F100-PW-100 Test Instruction Sheet", Volume 2 (revised 5/6/74, and are listed in Table 4 2.2-IV

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TABLE 4.2.2-IV

F100 GAS GENERATOR OPERATING LIMITS

Oil Inlet Temperature ~ °C (°F)

Normal Operating Range	38-149 (100-300)
Maximum (All Operation)	165 (330)
Maximum - Intermediate (During stabilization at idle following high power operation)	185 (365)

Turbine Cooling Air (Function of PC05/PB)

Chamber No 5 pressure/burner pressure with PC11/PB
Chamber No. 11 pressure/burner pressure

Ratio	Maximum	Minimum
PC05/PB	0.28	0.23
PC11/PB	0.85	0 70

Main Oil Pressure

Varies in proportion to compressor (N_2) speed and oil temperature The following main oil pressure limits shall be strictly adhered to.

Normal Operating Range (Relative to breather pressure)	13 8-55 N/cm^2 (20-80 psi)
Maximum Allowable for Oil Temperature Greater Than 4°C (40°F)	69N/cm^2 (100 psi)
Maximum Allowable Pressure Fluctuations	-13 8 N/cm^2 (± 20 psi)
Minimum (During starting and initial operation, not to persist for more than one minute)	13 8 N/cm^2 (20 psi)

Breather Pressure

Breather pressure shall not exceed 1 7 N/cm^2 (5 in Hg) at steady state conditions or during transient operation.

Vibration Limits

The maximum acceptable vibration limits throughout the complete operating range of the engine are tabulated below for the frequencies from 70 to 233 Hz

TABLE 4 2.2-IV (Cont'd)

Location	Maximum Single Amplitude
Inlet Case	0 0076 cm (3 0 mils) of which no more than 0 0025 cm (1 0 mil) shall be of the N_2 component
2-3 Bearing Compartment	0 005 cm (2 0 mils) of which no more than 0 0018 cm (0 7 mil) shall be of the N_2 component
Engine Gearbox	0 0064 cm (2 5 mils) of which no more than 0 005 cm (2 0 mils) shall be of the PTO component
Diffuser Case (horizontal, steady state only)	0 005 cm (2 0 mils) of which no more than 0.004 cm (1 5 mils) shall be of the N_1 component

During starts, the allowable limit is 0 019 cm (7 5 mils) single amplitude at all locations which must decrease to within the above limits within 5 seconds after attaining idle power

Fan Turbine Inlet Temperature (FTIT)

At intermediate power and above, the limits shown in Figure 4 2.2-5 shall be observed

During starting do not exceed 593°C (1100°F)

Fan Speed (N_1)

The limits in Figure 4 2.2-6 shall be observed

Compressor Speed (N_2)

The maximum allowable speed is (13,400 rpm)

Burner Pressure

The maximum allowable pressure is 2100 N/cm^2 (580 psia)

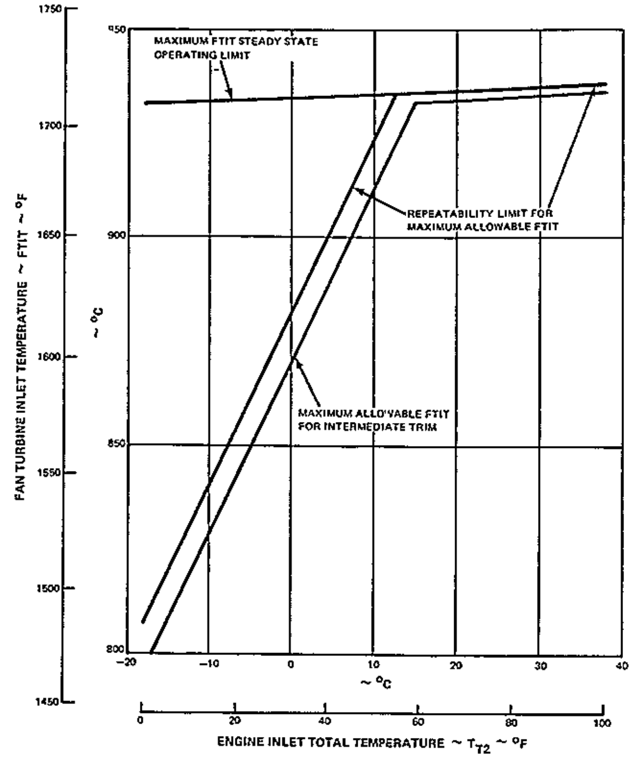

Figure 4 2 2-5 F100-PW-100 Fan Turbine Inlet Temperature Limit

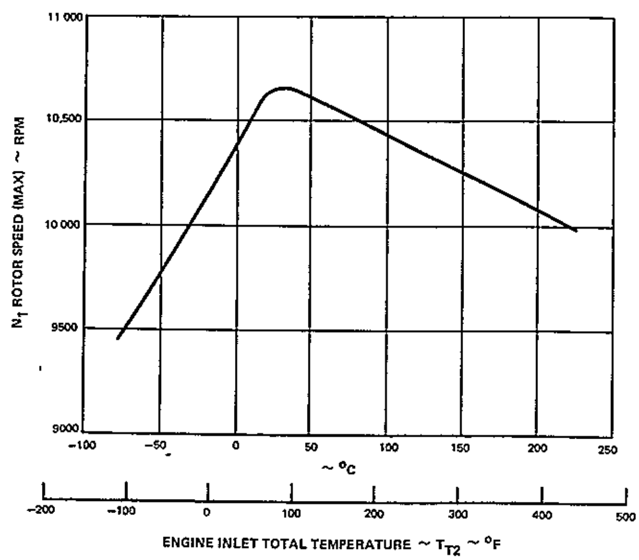

Figure 4 2 2-6 F100-PW-100 Engine Maximum Fan Speed Limits

TABLE 4.2 2-IV (Cont'd)

Compressor Inlet Variable Vanes (CIVV)

The boundaries shown in Figure 4.2 2-7 shall be observed

Rear Compressor Variable Vanes (RCVV)

The boundaries shown in Figure 4.2.2-8 shall be observed

Augmentor Spikes

Limit augmentor over-pressure spikes at the fan discharge to 10 percent of the steady state operating fan discharge pressure before augmentor lightoff

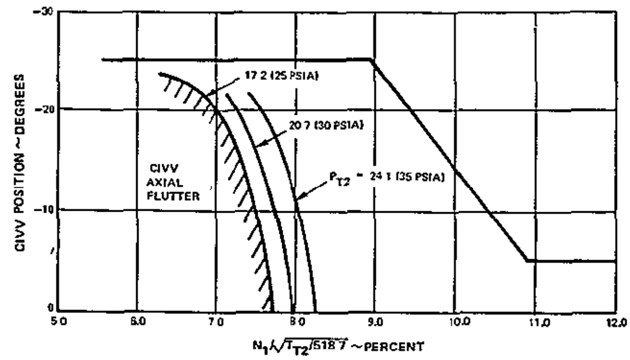

Figure 4 2 2-7 F100-PW-100 Engine Compressor Inlet Variable Vane Operating Characteristics and Limits

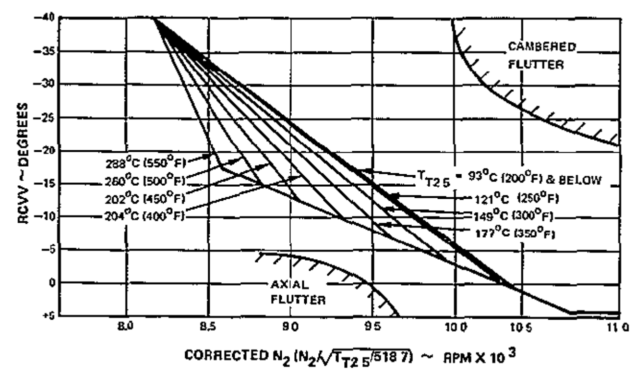

Figure 4 2.2-8 F100-PW-100 Engine Rear Compressor Variable Vane Operating Characteristics and Limits

Since the duct burner is to be designed, the established operating limits are in the form of controllable parameters Specific limits will be determined during the design analysis that will be accomplished in the following program phase

The duct burner liner temperature levels will be limited by the maximum allowable fuel-air ratio, and reliable ignition characteristics will be established by a minimum fuel-air ratio A duct corrected airflow upper limit will maintain operation below maximum liner buckling loads, while a lower limit will ensure adequate cooling air. In addition, a maximum duct nozzle throat area will be specified to prevent thermal choking upstream of the nozzle throat which could cause combustion instabilities

4.2.2.4 Exhaust Nozzle System Selection

Several exhaust nozzle designs used in existing Pratt & Whitney Aircraft engines were evaluated for potential application in the VCE testbed. These included the JT4 convergent flap nozzle, TF30-P-7 flap nozzle, TF30-P-412 iris nozzle, TF30-P-100 iris nozzle, F100 convergent-divergent nozzle, and F401 convergent-divergent nozzle

To assess the relative merits of each design, selection criteria were formulated to address the major considerations of nozzle size, mechanical and aerodynamic compatibility with the duct burner and F100 engine, and availability. The results of the evaluation are summarized in Table 4.2 2-V and discussed below.

Both the JT4 and F100 nozzle configurations were determined to be unacceptable on the basis of size The small size of these nozzles would produce interference with duct burner hardware.

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TABLE 4 2 2-V

CANDIDATE EXHAUST NOZZLE SYSTEMS AND SUMMARY

JT4	–	Size too small
TF30-P7	–	Aero/mechanical incompatibility
TF30-P412	–	Aerodynamic incompatibility
TF30-P100	–	Acceptable but unavailable
F100	–	Size too small
F401	–	Acceptable

The TF30-P-7 nozzle design was rejected as a result of aerodynamic/mechanical incompatibility. With this design, the nozzle actuator system is mounted inside the ejector supports or *"stings"*, which are beam-like structures located in six places The linkage system utilizes pivot points that are integral with the ejector support ring at the ends of the sting structures However, in the VCE configuration, using this arrangement to support the ejector is not a viable approach since the ejector inlet area would be neither correct nor variable Nozzle variability is a prerequisite for the testbed configuration.

The TF30-P-412 nozzle was shown to be unacceptable because of aerodynamic considerations With this particular nozzle geometry, a cylindrical throat section at the exit area of the nozzle makes it difficult to establish the nozzle location when the inner body structure is superimposed on the system The definition of this throat location is a requirement for the testbed.

The TF30-P-100 iris nozzle shown in Figure 4.2.2-9 was determined to be acceptable in terms of all criteria except availability. The possibility of procuring this type of nozzle for the testbed program was investigated and indicated to be essentially negligible because all spares in the Air Force inventory are needed to support service engines. Consequently, the F401 exhaust nozzle was selected for the VCE testbed.

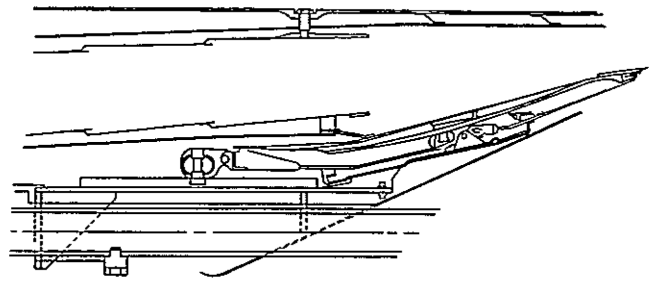


Figure 4.2 2-9 TF30-P-100 Exhaust Nozzle - This nozzle, as shown installed in the testbed, is mechanically and physically compatible

The F401 convergent-divergent nozzle configuration is shown in Figure 4.2.2-10. This nozzle is similar to the F100 design, but physically larger in size. For the testbed configuration, the nozzle would be modified by removing the divergent portion of the nozzle. Other minor modifications would be required such as installing an aerodynamically-designed fairing over the actuator linkage to eliminate a potential noise source when the ejector is used

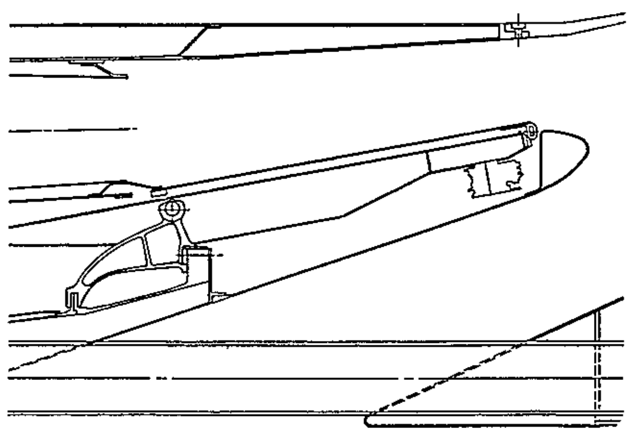


Figure 4.2.2-10 F401 Exhaust Nozzle - This nozzle system has been selected for the VCE testbed.

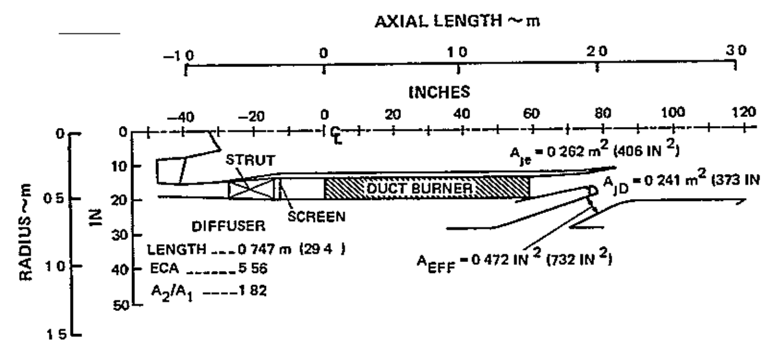
4.2.2.5 Testbed Conceptual Mechanical Configuration

Before initiating the mechanical design of testbed hardware, an aerothermodynamic flowpath was completed This procedure ensures that all component design assumptions and hardware interfaces are examined prior to beginning the final design effort.

Predicted testbed engine performance levels defined the gas flows, temperatures, and pressures throughout the duct burner and exhaust nozzle system On the basis of these design conditions, the flowpath shown in Figure 4.2.2-11 was constructed. Critical areas, Mach numbers and pressures were checked against performance assumptions, and necessary adjustments were made for component predictions based on preliminary design efforts.

With definition of the flowpath, the conceptual mechanical configuration of the testbed engine was established, showing the interface of the F100 core engine with the testbed and identifying hardware requirements. A cross section of the testbed engine system is shown in Figure 4.2.2-12. The interface between the F100 engine and the testbed is at the trailing edge of the engine turbine exhaust case and the rear fan duct case flange. The mixed-flow afterburner and the single-stream nozzle of the F100 have been removed for installation of the duct burner, modified F401 exhaust nozzle, and acoustically-treated ejector. Existing inlet hardware for the F100, including the screen and calibrated bellmouth, will be supplied for the program by the Government Products Division

As part of the preliminary mechanical definition, the major component subsystems in the testbed were reviewed from a thermal-mechanical standpoint to identify potential problem areas resulting from integration of the F100 engine with the testbed. This review included the following subassemblies: engine exhaust cone, turbine exhaust case/inner duct interface, strut case and inner duct, antidistortion screen, primary fuel manifold, duct burner, exhaust nozzle, and ejector. A discussion of each of these subassemblies indicating the areas to be addressed during the detail design is presented in the following paragraphs



STATION IN/M	−42/−1 067	−12 5/−318	0/0	75/1 91	83 5/2 12	110/2 79
DESCRIPTION	DUCT DIFFUSER INLET	PRIMARY TAIL PIPE ENTRANCE	DUCT BURNER ENTRANCE	DUCT STREAM THROAT	PRIMARY THROAT	EJECTOR
T_t, °R/°K	772.9/429 4	1492 3/829 1	772 9/429 4	3060/1700	1492 3/829 1	
P_t, PSIA/(10^{-5} N/m^2)	40 5/2.79	23 89/1 65	39 27/2 71	33 9/2 34	23 28/1 61	
A, IN^2/M^2	378/ 244	480/ 310	686 4/ 443	373/ 241	406/ 262	1425/ 91
WA PPS/KG/SEC	110 75/50 23	121 75/55 22	110 75/50 23	110 75/50 23	121 75/55 22	

Figure 4.2 2-11 VCE Testbed Flowpath - Areas, flowrates, pressures, and temperatures are listed for the duct stream nozzle throat, primary stream nozzle throat, and ejector.

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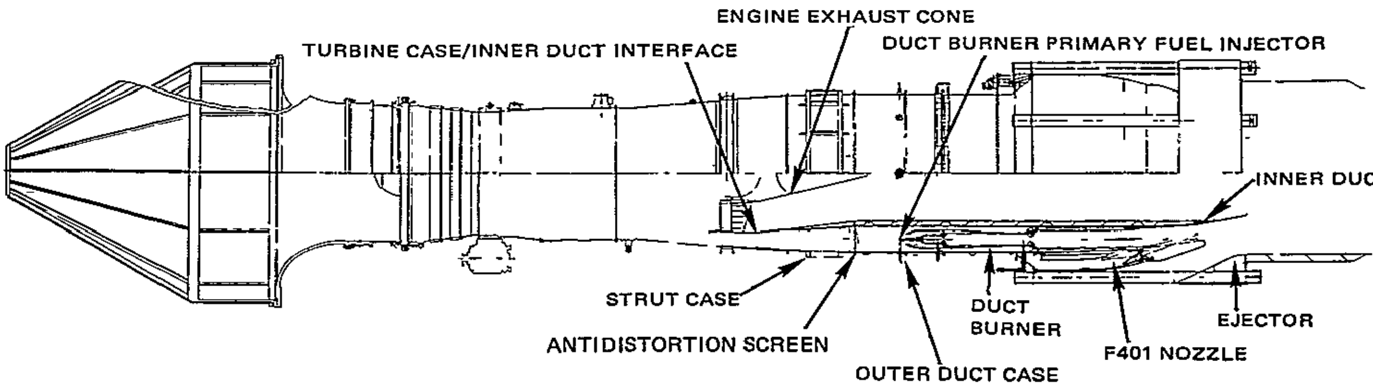

Figure 4.2.2-12 Testbed Cross Section - The mechanical configuration of the testbed engine is shown in the test condition, complete with the inlet screen and bellmouth and ejector.

Engine Exhaust Cone

The exhaust cone in the F100 engine, as shown in Figure 4.2.2-12, is a truncated configuration. Since this could be a source of noise because of the separation of airflow as it flows past the lip of the cone, the cone will be reconfigured to a full cone shape to eliminate this potential noise source A review of vibratory modes and buckling characteristics would be required.

Turbine Case and Inner Duct Interface

Since the F100 engine is a single-stream system, there is no requirement for the turbine exhaust case outer shell segments to sustain a large pressure gradient. In the testbed configuration, a pressure gradient will exist because the air streams are not allowed to mix. As a result, at the interface between the turbine exhaust duct and inner duct, a sheet metal wall with a mechanical slip joint scheme is required to withstand the pressure gradient and to allow for thermal expansion in the axial direction.

Strut Case and Inner Duct

The strut case supports the inner duct structure. Structural areas associated with this assembly that will require attention include: establishing fatigue and vibration limits, defining the number of struts to support the inner duct, and identifying a solution to thermal incompatibility between the core and duct streams.

Similar areas requiring design effort were also disclosed for the inner duct. These include. potential axial and radial thermal incompatibilities between the inner and outer walls, the effects of acoustically-induced vibrations generated by the duct burner, buckling characteristics, and panel vibration characteristics of the sheet metal sections.

Antidistortion Screen

The antidistortion screen is located in the fan duct stream in back of the inner duct support struts. Functionally, this screen serves to minimize aerodynamic distortions generated upstream from obstructions and irregularities in the fan duct. From a structural standpoint, the screen does not present any unique design problems since it is a nonsupporting member.

Primary Fuel Manifold

The primary duct burner fuel injector, as shown in Figure 4.2.2-12, penetrates the flowpath at the entrance to the duct burner prechamber stage. Because of this projection into the air stream, the fuel manifold design will account for vibration resulting from an aerodynamic excitation forces.

Duct Burner

A main design consideration for the duct burner is to account for the large thermal gradient across the louvered liners. The liners will be designed to operate at average metal temperatures of 760°C (1400°F) and be exposed to hot streak metal temperatures of 860°C (1600°F) However, the duct burner will operate with an inlet airflow temperature of 204°C (400°F), in contrast to the substantially higher compressor discharge temperature of 537°C (1000°F) normally used for the main combustor. The effect of this lower temperature inlet flow is that the thermal gradients are higher than those in the primary burner In addition to the high thermal gradients across the liner structure, the design must address low-cycle fatigue and buckling considerations

Exhaust Nozzle

The F401 nozzle, as designed for its normal application in the F401 engine, is a convergent/divergent system with a pressure flap connected to the convergent (balanced beam) section to reduce nozzle actuation load requirements However, the nozzle for the testbed configuration, as shown in Figure 4.2.2-12, will be installed in a *"bob-tailed"* condition This means the divergent section of the nozzle is removed, leaving the pressure flaps and balanced beam flaps (convergent section) This exposes the actuation linkage on the back side of the balanced beam and creates the requirement for an aerodynamic fairing when the ejector is evaluated The use of a fairing eliminates the potential noise source of the exposed linkage and provides a positive dimensional control of the ejector inlet area The fairing is a nacelle type structure. Analyses will be required to ensure that all acoustical requirements have been satisfied

Ejector

The ejector is supported on five pipe supports that simulate blockage from an equivalent flight engine structure The component is adjustable in the axial direction to provide a variable ejector inlet throat area which can be increased by approximately 30 percent. An acoustically-treated liner provides the flowpath liner and can be replaced with an untreated liner The design of the ejector will be centered on resolving vibration and thermal incompatibilities associated with a double wall structure, and to ensure that the inlet to the ejector is designed to avoid airflow separation.

Testbed Materials Selection

A materials selection for the testbed has been made on a preliminary basis The selection of materials is based on availability as well as experience to ensure component reliability and durability for the test program

The major portion of the testbed structure will be fabricated from 410 martensitic corrosion resistant steel and AM363 martensitic stainless steel. This includes such components as the strut case, outer duct case, and ejector system. An advantage with AM363 material is that heat treatment is not required This eliminates an extra fabrication process and problems associated with distortion of heat-treated materials.

Hastelloy X, a nickel base alloy, has been selected for the combustor liners in all three zones as well as the rear flange and the innermost portion of the inner duct subassembly that is exposed to the gas flow from the core engine. Extensive experience with the use of this material for hot section applications has served as a basis for selection The material has a high temperature capability, good creep strength and oxidation-corrosion resistance, in addition to excellent forming and joining qualities.

The swirler tubes at the entrance to the second and third combustion stages will be fabricated from Stellite 31, a cobalt alloy being used in the duct burner rig test program under contract NAS3-20602.

4.2.2.6 Testbed Assembly Considerations

The mechanical design definition also addressed the aspect of testbed assembly to ensure that the program objectives can be met with a minimum loss in time during the test program. The testbed design is based on a modular construction concept which offers the inherent advantage of facilitating assembly and disassembly operations.

One major advantage of component modularity is that it allows the complete instrumentation of each module before final assembly, thereby reducing the complexity and time expenditure for instrumentation checkout and data acquisition. For the testbed, the design philosophy is to integrate the instrumentation with the structural components. Consequently, individual modules can be removed for modification and/or repair of either the instrumentation or the component without cutting and replacing instrumentation.

The modular component assembly of the testbed is accomplished in six steps, as depicted in Figure 4.2.2-13. As shown in Step 1, the strut case is the primary structure The case structure with the integral, antidistortion screen and primary fuel nozzle is then added to the strut case, as indicated by Step 2. Next, the inner duct structure is joined to the assembly (Step 3). Also, the fairing is installed after the instrumentation lead wires are routed through the support strut and strut case

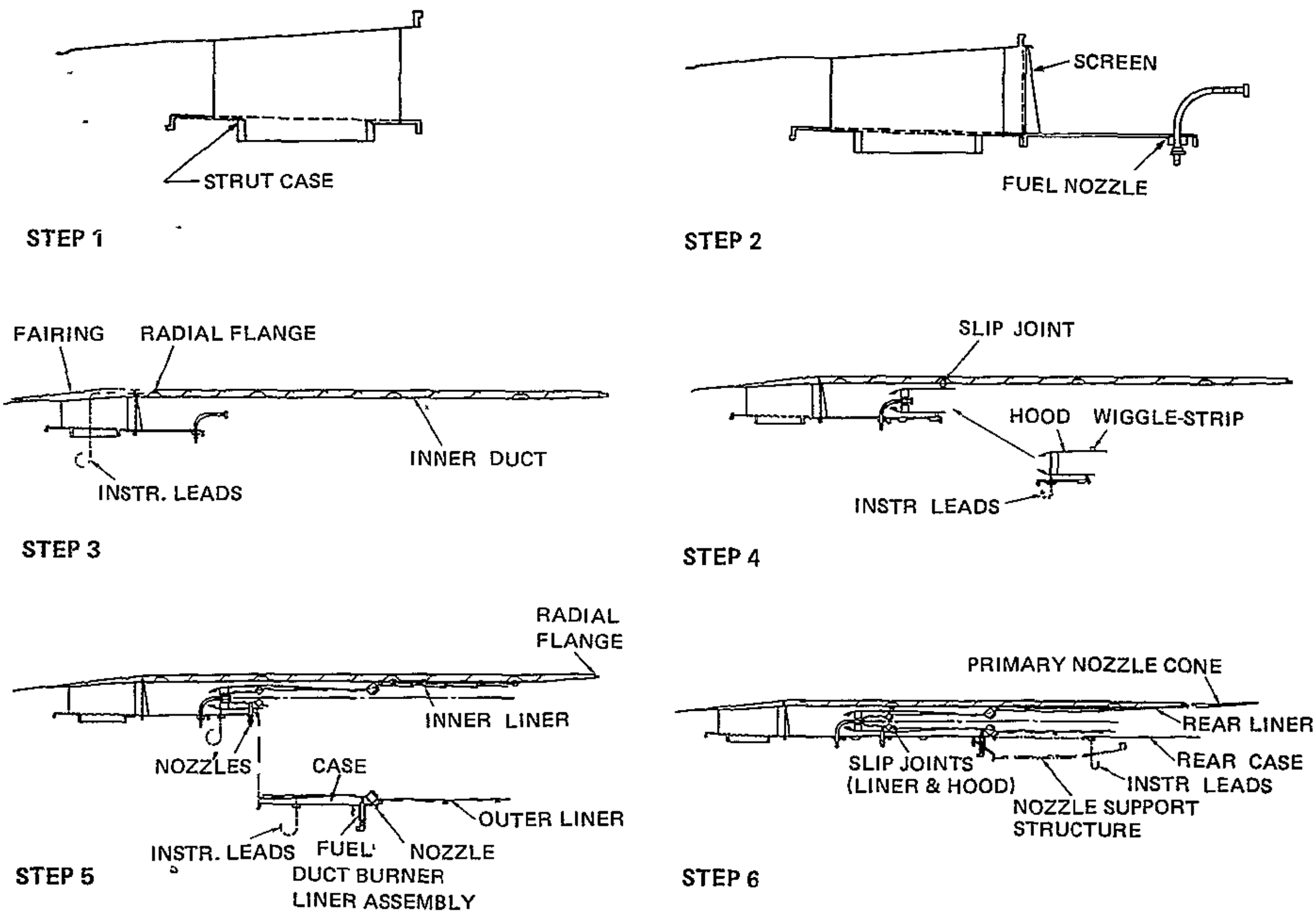

Figure 4.2.2-13 *Testbed Assembly Procedure – The sequence of figures illustrates how the different modules are assembled in a six step process. Note the provisions for instrumentation lead wiring in different component modules*

Assembly of instrumentation and installation of the duct burner components is then started. In Step 4, the hood structure and outer case subassembly is added to the major assembly. With assembly of the hood, the inner duct burner liner is joined to the assembly Similarly, the outer liner, complete with fuel nozzles, main outer case and instrumentation leads from the liner is installed in Step 5 The final step (Step 6) consists of adding the rear case, positioning the rear liner and attaching the primary nozzle cone at the radial flange, and installing the nozzle support structure. In Step 6 of Figure 4.2.2-13, the nozzle support contour is represented by dashed lines in order to indicate the final position.

4.2.2.7 Testbed Mounting and Installation Approach

Two methods were investigated for mounting the testbed engine These approaches are shown in Figure 4.2.2-14, and consist of a three-plane mounting system and a two-plane system

A three-plane system was initially considered since this approach eliminated the concern of a potential vibration problem that could be encountered if the testbed was left unsupported Also, this method offered a greater margin to accept weight increases that could occur from the type of construction used for the testbed. However, further analysis of the three-plane system disclosed several problem areas that made it unattractive for this application.

Analyses indicated that the three-plane system produced an unacceptable change in loads on the F100 engine thrust mount. This was the result of the duct burner, nozzle, and ejector thrust loads being taken out through the mount above these components rather than the F100 mounts. In addition, the third mount would require modification of test site hardware These modifications would involve an extension of the mounting strongback which supports the engine.

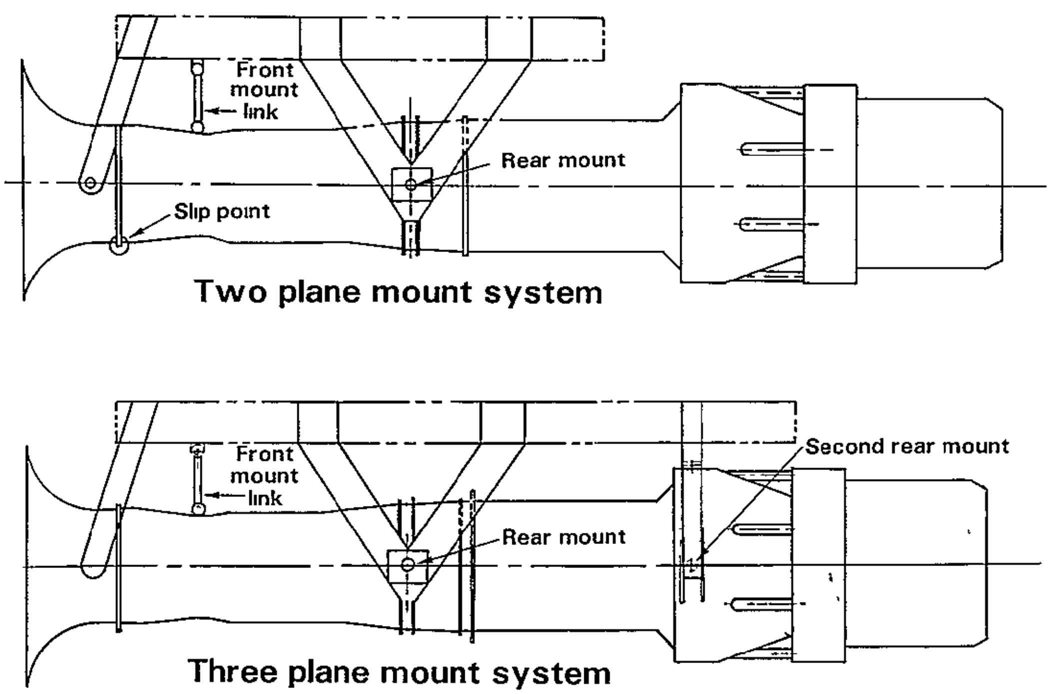

Figure 4 2 2-14 Candidate Testbed Engine Mounting Schemes - The two-plane system, which uses the F100 mount system to support the testbed, is the selected approach

The two-plane mounting approach, as shown in Figure 4.2.2-14, has the testbed cantilevered from the rear fan duct of the F100 engine. The F100 engine mount system is utilized for supporting the entire testbed system. The front mount on the F100 is a single-point connection located on the top vertical centerline of the engine. This mount point is designed for vertical loads, while also having the capability to support minor side loadings. The rear mount consists of a two-point connection located on the horizontal engine centerline These mount points are capable of sustaining both thrust and vertical loads. A side load connection point is also located in the lower quadrant of the rear mount ring. The system was reviewed analytically to determine the effect of the duct burner, nozzle, and ejector overhung mount and resonant vibration on the F100 engine structures The areas of concern were bending of the F100 engine/testbed interface flange, buckling of the rear fan case, and unacceptable case loads The results of this analysis indicated that vibration levels and the mechanical loadings on the F100 structures were well within allowable limits.

On the basis of the problems identified with the three-plane system and the structural acceptability of the two-plane system, the two-plane mounting system was selected for the testbed engine.

4.2.3 Control System

4.2.3.1 Control System Requirements

The testbed configuration, which utilizes a three stage duct burner and variable coannular nozzle system installed behind a F100 engine, imposes a special requirements for the control system. These include.

- Stable operation of the engine and duct burner over the entire range of testbed operating points, and ensure engine and duct burner operational limits are not exceeded
- Independent metering of each stage of the duct burner fuel flows
- Controlled transition between engine and duct burner operating points
- Protection of the testbed system from potential failures
- Ease of operation

Each of these requirements is discussed in greater detail in the following paragraphs Because of the anticipated number of test points planned during the test phase of the program, it is desirable that the control system has the capability to accomplish these functions as efficiently as possible in order to minimize the operating time of the F100 engine

Stable Operating Point Control

In order to achieve the desired test operating points for acquisition of noise and exhaust emissions data, the control system must ensure control of the compressor inlet variable vanes (CIVV), the rear compressor variable vanes (RCVV), the compressor bleeds, the main burner fuel flow (WFE), the duct burner fuel flow (WFDB), and the duct exhaust nozzle area (AJD). Representative rematched operating points for the testbed are listed in Table 4.2 3-I. In this table, two rematched operating points of maximum airflow with two different primary stream nozzle areas are shown in comparison to the base F100 operating point As indicated, the control system is required to operate the F100 engine at significantly different match points from the base engine match. This has an impact on the capability of the base F100 control system to acquire all the rematched testbed operating points

TABLE 4.2.3-I

REPRESENTATIVE REMATCHED TESTBED OPERATING POINTS

	Low rotor speed (RPM)	High rotor speed (RPM)	Total airflow kg/sec (lbs/sec)	Duct airflow kg/sec (lbs/sec)	Core nozzle area m^2 (in^2)	Primary burner pressure N/m^2 (psi)	Primary burner fuel flow kg/sec (lbs/hr).
Base F100	10,113	13,033	103.0 (227)	40 8	–	2.482 x 10^6 (360)	1.342 (10,652)
Rematched	10,364	12,397	105.7 (233)	50 3 (111)	.262 (406)	2 069 x 10^6 (300)	942 (7480)
	10,331	12,536	105 7 (233)	49.0 (108)	226 (350)	2 137 x 10^6 (310)	1 018 (8077)

For repeatibility of operating points, it is desirable that the control system regulate the engine, duct burner and nozzle such that actual duct flow variations are within ±1 percent of the set point, regardless of the accuracy of actual airflow measurement used for performance data. In addition, the control system must protect the engine from exceeding the established operating limits These limits are fan turbine inlet temperature (FTIT), fan speed (N_1), compressor speed (N_2), burner pressure (PB), CIVV flutter boundaries, RCVV flutter boundaries, and fan and compressor surge limits The duct burner operating limits, discussed below must also be maintained

Duct Burner Fuel Flow Metering

Three fuel flows must be independently metered for the three-stage Vorbix duct burner configuration This independent fuel flow management scheduling includes the capability to vary individual stage fuel flows, while automatically maintaining constant value of total duct burner fuel flow The total duct burner fuel-air ratio must be capable of being varied from 0 002 to 0 043. A typical fuel-air schedule for the three-stage burner system is shown in Figure 4 2 3-1. In the light-off fuel-air ratio range, the fuel flow must be controlled to within ±5 percent of the set point in order to allow setting light-off fuel-air ratios to values on the order of 0.002 with an accuracy of ±0.0001. (For example, 5 percent = [0 0001* WDUCT/ (0.002* WDUCT)] * 100, where WDUCT = duct airflow.) In the maximum fuel-air range, fuel flow must be regulated to within ±1 percent of the set point to maintain accurate fuel-air ratio control.

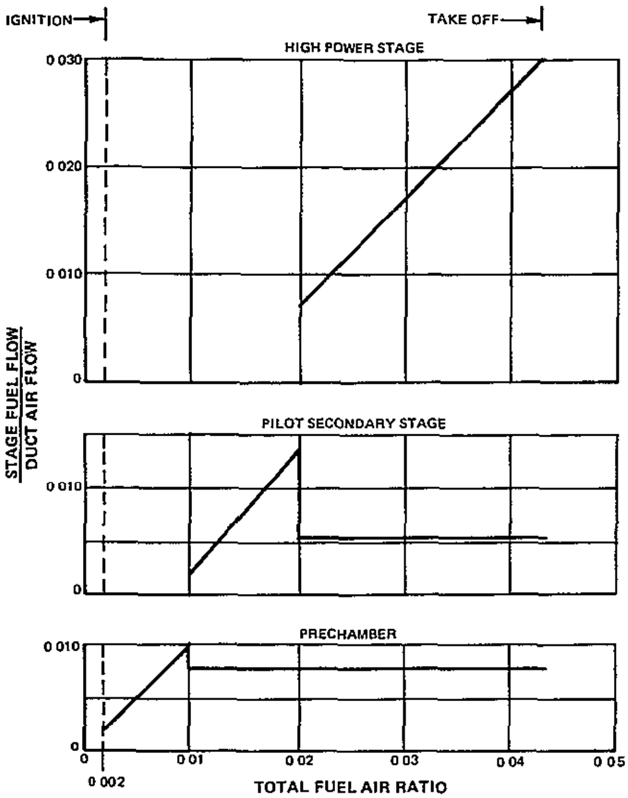

Figure 4 2.3-1 *Typical Fuel Schedule for a Three-Stage Duct Burner - This fuel schedule shows the fuel sequencing from ignition through to takeoff power, at which all three stages are operative.*

Controlled Transition Between Operating Points

To minimize the required time to change test operating points and thereby minimize test time, it is important for the control system to maintain control of the entire transition process This includes power lever inhibit logic during duct burner stage fill and light-off, and fuel flow rate limiting and stage sequencing These combine to avoid damage to the duct burner resulting from inadvertant rapid or excessive movements of the duct burner power lever

The control must provide an automatic nitrogen purge of stages after they are shut off in order to avoid coking problems. The coordination of main fuel flow, duct burner total fuel flow, and duct nozzle area must also be provided during all phases of operation to maintain engine and duct burner operating limits during operating point transition.

Transient Testing

A demonstration of duct burner transient operation may be required at the conclusion of the test program. The capability to provide automatic transient control of the engine and duct burner will be available as a result of the transition control capability, discussed in the previous paragraph.

Failure Protection

The control system must be able to maintain engine and duct burner operating limits in the event of failure such as that resulting from duct burner blowout, loss of control of duct fuel flow or nozzle area, loss of transducer, failure of any computer utilized in the control system, or loss of electrical power.

Ease of Operation

Since a substantial number of test operating points is planned for the technology demonstration testing, it is important that the control system ensure ease of setting operating test points. To accomplish this requirement, closed-loop control of each control variable will be implemented as a function of scheduled engine variables. Manual control and trim functions must also be incorporated to facilitate special test procedures such as investigating the fuel flow split between two duct burner stages

4.2.3.2 Bill-of-Material F100 Control System

Considering the requirements imposed on the control system for operating the testbed system, the bill-of-material F100 control system was evaluated to determine if it could satisfy these requirements. There are two primary elements in the F100 fuel system the unified fuel control (UFC) and the electronic engine control (EEC)

The unified fuel control regulates WFE, RCVV, augmentor fuel flow (WFAB), and exhaust nozzle area (AJ). The WFE is a proportional, or droop governor, control which operates as a function of the high-pressure rotor speed error. The RCVVs are scheduled as a function of high rotor corrected speed Total WFAB is scheduled versus a rate limited power lever and fan discharge temperature. The control system meters total WFAB according to this schedule, and a single splitter valve is used to control the split of fuel among the three core stream zones and the two duct stream zones of the mixed-flow augmentor. The AJ is scheduled as a function of rate limited power lever and fan discharge temperature. Manual ground trims are provided for the high rotor speed reference, RCVV schedule, AJ schedule, and WFAB schedule

The basic functions of the engine electronic control include regulation of the CIVVs, trimming the UFC power lever to reset WFE, and trimming the UFC AJ schedule The CIVVs are scheduled as a function of low rotor corrected speed. The trim on the UFC power lever operates at power lever angles of 83 degrees and above to reset the WFE in order to maintain accurate control of the high rotor speed to a scheduled value. This trim also operates at all power lever settings to reduce the UFC power lever, and thus WFE, in order to maintain operational limits on low rotor speed, high rotor speed, fan turbine inlet temperature, and burner pressure

The trim on the UFC AJ schedule operates at power lever angles of 83 degrees and above to reset the exhaust nozzle area in order to maintain accurate control of the low rotor speed to a scheduled value that is correlated to the desired airflow schedule. Manual ground trims are provided on the high rotor speed schedule and the fan turbine inlet temperature limit schedule.

On the basis of evaluation, it was determined that the bill-of-material F100 control system would not be suitable for the testbed system, without major modifications to the control First, the augmentor flow system was incompatible with the requirement to provide independent metering of three duct burner stage flows. Second, the bill-of-material system was determined to be marginal in providing sufficient manual trim range to operate the engine at the rematched operating points. Based on these considerations, work was directed towards evaluating alternative control system configurations for the testbed. The results of this evaluation are discussed in the following section

4.2.3.3 Testbed Control System Selection

In selecting a control system for the testbed, the main emphasis was to use as much as possible of the F100 bill-of-material control components available from previous test programs. A total of five alternate control configurations was evaluated.

A schematic diagram of the first two systems studied, configurations number 1 and 2, is presented in Figure 4 2.3-2. Overall, the two concepts meter total duct burner fuel by using UFC zone 1 flow and available percent split valves for independent regulation of the three duct burner stage flows.

Configuration 1 uses the bill-of-material control for all controlling functions except regulating the fuel flow split among the three duct burner stages. In this concept, four of the five augmentor flow pipes are capped, and the zone 1 flow section affords metering of total duct burner flow. The two percent split valves shown in Figure 4.2.3-2 are then controlled by a Real Time Control Simulation (RTCS) computer for independent metering of the

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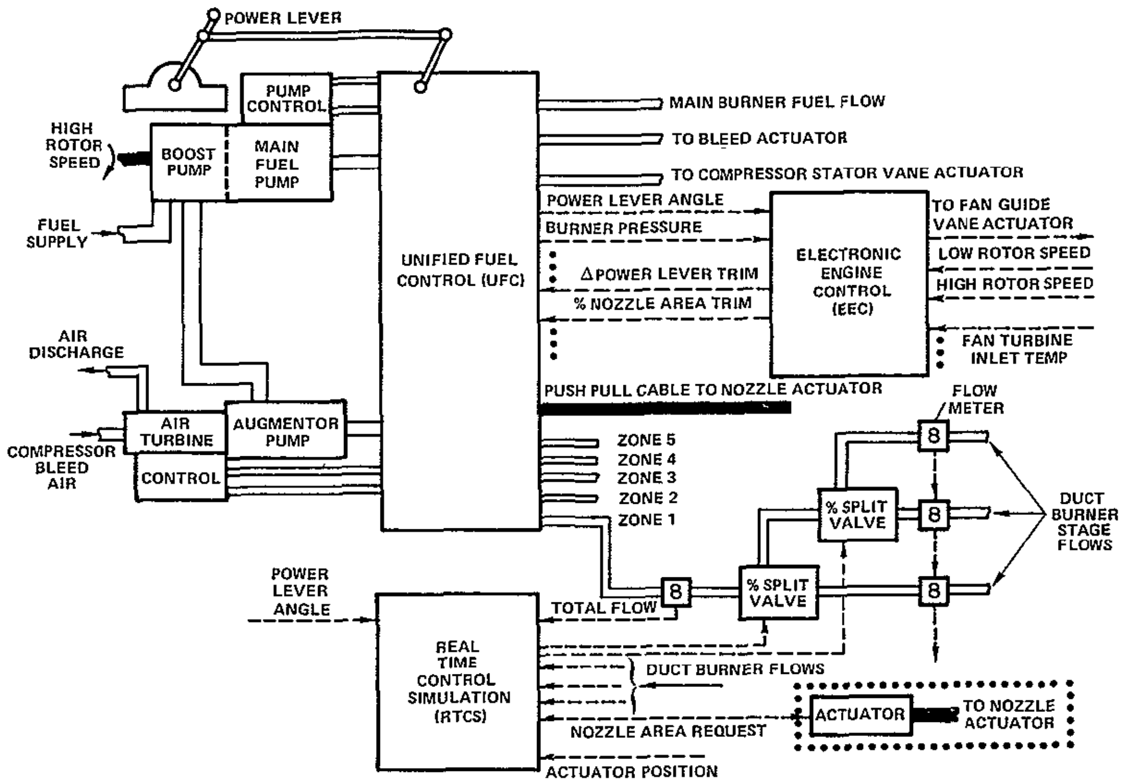

Figure 4 2 3-2 Control Configurations 1 and 2 - Both configurations meter total duct burner fuel flow by using UFC zone 1 flow and available percent split valves for independent stage flow regulation.

flow to the respective duct burner stages. The RTCS is a minicomputer with appropriate interface devices for sensing engine variables and driving control actuators In addition, the RCTS incorporates a control panel with push button inputs and a digital display that can be set up to perform all control mode selection and trimming functions required to facilitate the test procedures. This first control configuration was not selected for the testbed application since the scheduling for the exhaust nozzle area (AJ) in the bill-of-material control did not provide sufficient flexibility for the test program

Configuration number 2 uses a separate actuator controlled by the RTCS to drive the push - pull cable connected to the nozzle actuation system, in contrast to the earlier concept. Further assessment of this system, however, disclosed that substantial modifications would be required in the UFC to use the zone 1 flow system for metering the duct burner fuel flow Moreover, continual resetting of the manual trims would be necessary for obtaining each test operating condition, and several operating conditions were identified which could not be obtained with these trims. Finally, it was desired to operate the duct burner fuel section of the UFC. The bill-of-material augmentor fuel pump can supply these higher pressure levels. On the basis of these factors, this concept was eliminated from further consideration.

The third configuration evaluated is similar to the second control concept with the exception that a separate electric motor-driven, positive displacement pump and a modified JFC25 fuel control are utilized to meter total duct burner fuel flow. A diagram of this control system is shown in Figure 4.2.3-3.

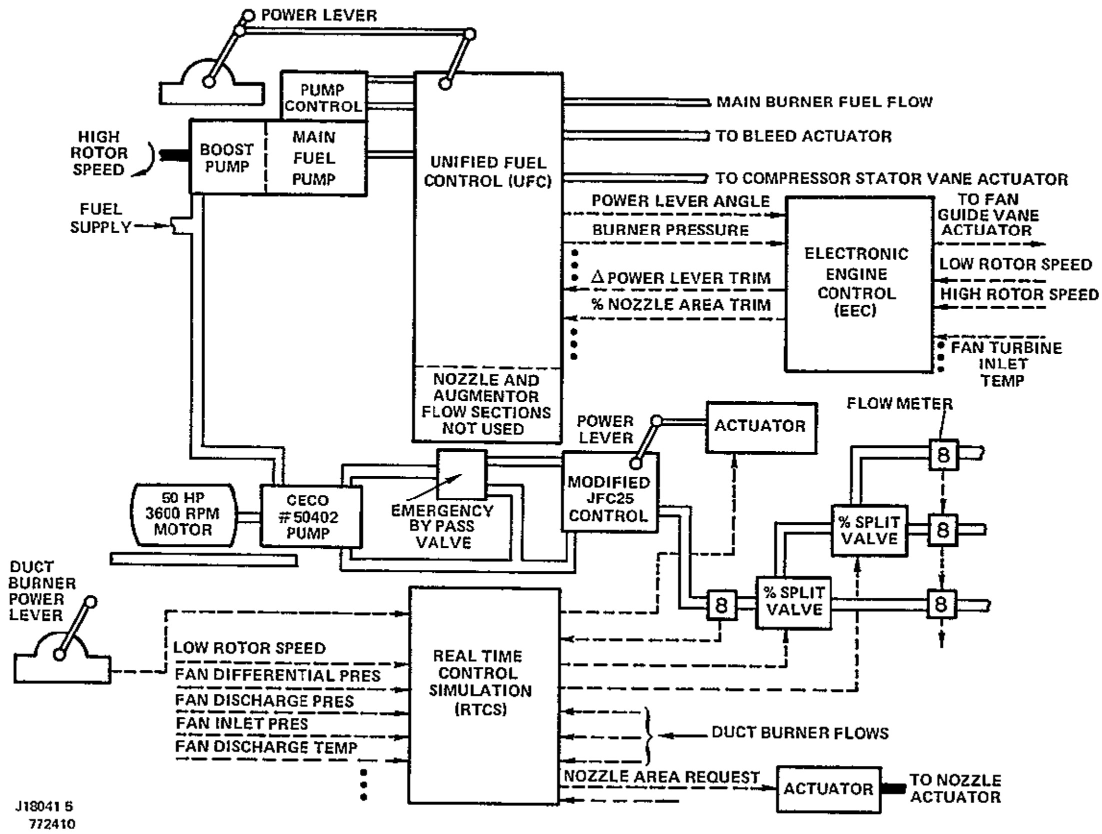

Figure 4 2 3-3 Control Configuration 3 - This configuration is similar to the second configuration except a motor driven pump and modified JFC25 fuel control are used to meter the total duct burner fuel flow

The modification to the JFC25 control would allow it to function simply as a metering valve, controlled by the RTCS, for the total required fuel flow As with configuration 2, the RTCS also controls the two percent split valves and the exhaust nozzle actuator. A separate power lever controls the gas generator through the UFC, and another power lever controls the duct burner through the RTCS. Although the motor-driven pump and the modified fuel control provided the required pressure levels in the duct burner fuel system not attainable by the second configuration, the third concept was not selected because of the advantage offered by configurations number 4 and 5. Both of these concepts utilize the bill-of-material F100 augmentor fuel pump

A diagram of control configurations number 4 and 5 is shown in Figure 4 2 3-4. The key to these configurations is the availability of a TF30 afterburner flow cart. This flow cart has five separate metering valves, and when supplied fuel from a centrifugal pump such as the F100 augmentor pump, independent metering of five fuel flows can be accomplished Three of these metering valves are controlled by the RTCS to satisfy duct burner metering requirements. This flow cart can be operated at the higher fuel pressures desired for duct burner operation. Only minor modifications to the UFC and fuel system plumbing are required to supply pump control signals shown in Figure 4 2 3-4 Similar to the other configurations evaluated, the RTCS controls the exhaust nozzle actuation system which allows implementation of a closed-loop control to trim the nozzle area. This provides the capability to maintain the desired fan operating point as indicated by a fan pressure ratio or differential pressure parameter.

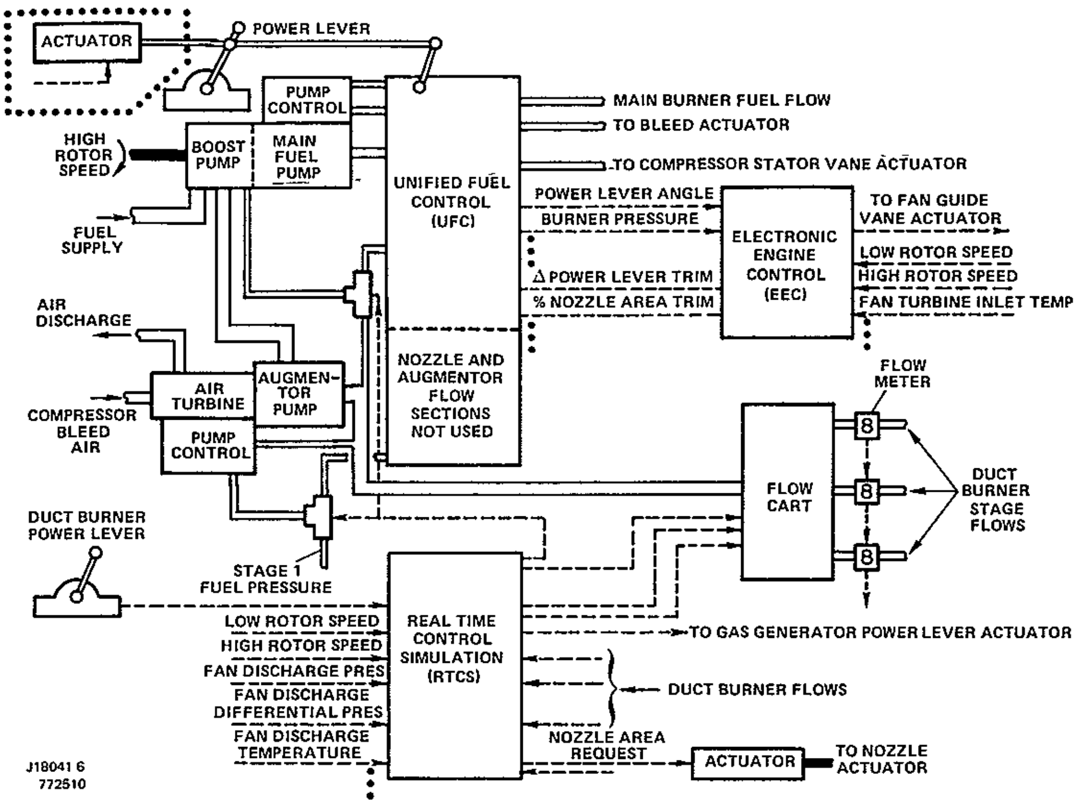

Figure 4 2.3-4 *Control Configurations 4 and 5 - These configurations utilize the bill-of-material F100 augmentor pump and a TF30 afterburner flow cart. Configuration 5 is the selected approach, and differs from configuration 4 in that an actuator, controlled by the TRCS, drives the UFC power lever.*

Configuration 4 uses the UFC to control WFE proportional to high rotor speed error Consequently, this approach does not exercise direct control over fan speed and would make it difficult to maintain duct airflow within the desired ± 1 percent of the set point To correct this problem, configuration 5 employs an actuator, controlled by the RTCS, to drive the UFC power lever. This approach has been successfully used in previous test programs and allows a closed-loop control function to be implemented in the RTCS to trim the UFC and obtain the desired low rotor speed. With this configuration, the UFC power lever angle will typically be less than 83 degrees so the EEC will only interface with the UFC to downtrim the power lever for engine limiting protection.

For control of the testbed engine, duct burner and nozzle, configuration 5 was selected This configuration offers a practical and reliable system for meeting the testbed program requirements. Table 4 2.3-II presents a summary of the features of this control system.

TABLE 4.2.3-II

FEATURES OF THE SELECTED TESTBED CONTROL SYSTEM

F100 Gas Generator and Augmentor Fuel Pumps	
F100 Unified Fuel Control With Minor Modifications	
• Main Burner Fuel Flow	Proportional (Droop Governor) Control as Function of High Rotor Speed
• Rear Compressor Variable Vanes	Scheduled Versus High Rotor Corrected Speed
• Augmentor Fuel Flow	Not Used
• Exhaust Nozzle Area	Not Used
F100 Electronic Engine Control With Modifications	
• Trim on UFC Power Lever	Trim Active for Maintaining Engine Limits
• Trim on UFC Exhaust Nozzle Schedule	Not Used
• Compressor Inlet Variable Vanes	Scheduled Versus Low Rotor Corrected Speed
Real Time Control Simulator	
• Exhaust Nozzle Area	Manual Control or Closed-Loop Control on Fan Pressure Ratio or Fan Discharge $\Delta P/P$
• UFC Power Lever	Manual Control or Closed-Loop Control on Low Rotor Speed
• Duct Burner Fuel Flows	Manual Control of Three Stages or Scheduled Versus Power Lever with Trim
TF30 Afterburner Fuel Flows	Independent Metering of Three Stages on Command from RTCS

4.2.3.4 Testbed Control System Design Requirements

The detailed design of the testbed control system involves several requirements. These include:

- Defining specific hardware modifications
- Establishing specific operating limits and test procedures
- RTCS control logic
- Failure mode and effects analysis (FMEA) and resulting failure logic
- Simulation evaluation
- Closed loop bench test

These requirements are to be addressed in the design analysis and detailed design phase of the Testbed Program to prepare the control system for use on the testbed engine The closed-loop bench test will provide a complete operational check of all control system components operating in a closed loop environment, utilizing a digital real time simulation of the testbed engine This will ensure safe, reliable operation of the system prior to actual engine testing.

4.2.4 Instrumentation Requirements

Instrumentation is a key element in the testbed design definition, and must be selected and located throughout the test configuration in such a manner to ensure acquisition of representative and meaningful data The instrumentation requirements for the testbed include. (1) the types of different sensors that will be used during testing, (2) instrumentation for monitoring the engine match point, performance and "health" of the F100 engine; (3) measurement requirements for noise and emissions data; (4) safety instrumentation; (5) control instrumentation, and (6) data validity. Each of these categories is discussed in the following sections.

4.2.4.1 Sensor Types

To determine the type of test instrumentation required for obtaining meaningful noise and emissions data, specific parameters of interest must be selected The test matrix for the testbed program is within the range of parameters shown in Table 4 2 4-1. The types of sensors to measure these parameters have been selected as part of the design definition.

Temperature levels will be measured by chromel/almuel thermocouples Pressure measurements will be acquired by static taps, keilhead probes, and water-cooled Kulite probes. Mechanical rotor speed will be monitored by magnetic proximity pick-ups, and vibration will be measured by accelerometers. Turbine meters will be used for monitoring fuel flow. The exhaust velocity of the core and duct streams will be measured by a laser doppler velocimeter. Exhaust emissions, including oxides of nitrogen, carbon monoxide, unburned hydrocarbons, and smoke, will be collected with a steam-cooled choked venturi Noise data will be acquired with highly sensitive microphones.

Although establishing the quantity of sensors at each engine station was beyond the scope of effort in the Planning and Definition Study, the quantity will be determined on the basis of the needs for obtaining a representative sample, impact on mounting and assembly/disassembly of the components, recording system capability, and engine operating time at the test site locations

TABLE 4.2 4-I

RANGE OF TEST PARAMETERS

Parameters	Range
Fan nozzle velocity ~m/sec (ft/sec)	365 to 883 (1200 to 2900)
Primary nozzle pressure ratio	1 3 to 1.7
Primary nozzle temperature ~°C (°F)	593 to 704 (1100 to 1300)
Primary nozzle velocity ~m/sec (ft/sec)	396 to 548 (1300 to 1800)
Thrust ~N (lbs)	31080 to 75480 (7000 to 17,000)
Primary burner fuel flow ~kg/h (pph)	91 to 3628 (200 to 8000)
Duct burner fuel flow ~kg/h (pph)	317 to 7256 (700 to 16,000)
Total airflow ~kg/sec (lb/sec)	68 to 113 (150 to 250)
Duct/core engine velocity ratio	0.8 to 2.0
Duct/core engine nozzle area ratio	0.5 to 1 2
Fan nozzle pressure ratio	1.9 to 2.3
Fan nozzle temperature ~°C (°F)	148 to 1426 (300 to 2600*)

*Peak gas temperature to be measured may be as high as 1704°C (3100°F)

4.2.4.2 F100 Engine Instrumentation

In order to obtain accurate test data for the duct burner and the coannular nozzle, the performance and operating conditions of the F100 engine must be measured. Of particular importance are the inlet and exhaust conditions to determine duct burner inlet airflow. The required test instrumentation for the F100 engine is depicted in Figure 4.2.4-1.

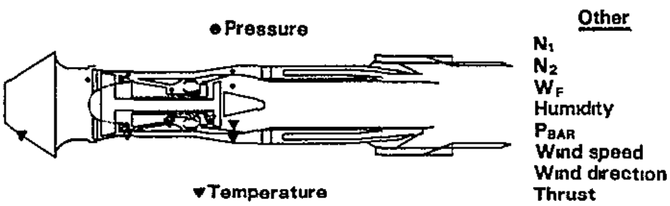

Figure 4.2.4-1 F100 Engine Instrumentation – In order to define the test points of the testbed, it is necessary to determine how the F100 engine is performing.

4.2.4.3 Noise and Emissions Instrumentation

The instrumentation for acquiring noise and exhaust emissions measurements, exclusive of the array of external microphones for noise, is shown in Figure 4.2.4-2.

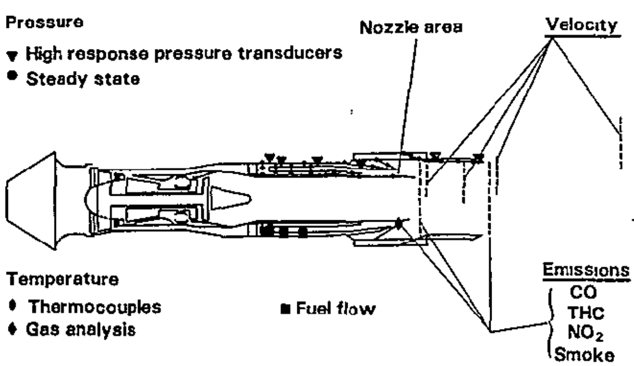

Figure 4.2.4.2 Noise and Emissions Instrumentation – As shown, the duct burner and ejector are heavily instrumented with both steady state and high response pressure sensors to document the flow conditions.

Water-cooled Kulite pressure probes will be installed at several locations in both the duct burner liner and the ejector wall for a discrimination of duct burner noise and jet noise levels. Velocity measurements of the core and duct stream exhausts will be made directly at the exhaust planes at several diametral stations downstream, as shown in Figure 4.2.4-2, as a diagnostic tool to confirm the noise benefit associated with the coannular, inverted velocity profile. The velocity measurements will be acquired with the Pratt & Whitney Aircraft laser doppler velocimeter system. The optics of this system will be modified to allow measurements particularly in the interface areas between the duct burner and core engine gas flow streams up to eight diameters downstream of the nozzle exhaust planes.

The estimated hot spot at the duct burner discharge plane exceeds the upper limit for the use of the thermocouples. Therefore, the emissions rake will be used to sense total pressure and collect a gas sample from the stream for analysis to compute gas temperature and for measurements of oxides of nitrogen, carbon monoxide, unburned hydrocarbons, and smoke. The design of this emissions sampling rake will take into consideration mounting and positioning the sensors, in addition to quenching the sample without condensation through the switching and mixing prior to analysis in the Pratt & Whitney Aircraft mobile laboratory.

4.2.4.4 Safety Instrumentation

The safety instrumentation for both the F100 engine and testbed is shown in Figure 4.2.2-3. Standard vibration instrumentation used on production and development F100 engines will be retained and monitored throughout the test. Vibration limits will be maintained at the current F100 levels.

Additional vibration instrumentation on the testbed engine, as indicated in Figure 4.2.4-3, will serve to monitor and limit dynamic amplitudes at frequencies below the rotor speed

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range. Although it is not anticipated, this instrumentation will ensure that potentially damaging vibration excited by burner noise or rumble is identified

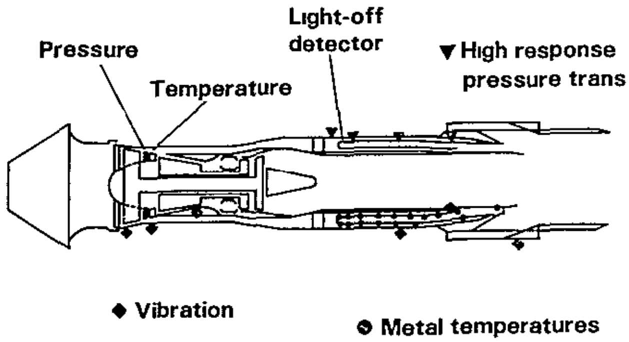

Figure 4 2 4-3 *Safety Instrumentation – This instrumentation will monitor temperature, pressure, and vibration levels to ensure that the F100 and testbed operate within safe limits.*

Condition monitoring instrumentation will be installed on the outer and inner testbed structures for monitoring and limiting vibratory amplitudes to levels consistent with the capability of the structure at the interface with the core engine. This instrumentation will also be used to limit the vibratory amplitudes of the inner case of the testbed relative to the outer wall to ensure that the allowable loading of the inner case support structure is not exceeded as a result of excitation from the F100 rotors, or from the lower frequencies generated by the burner.

Many thermocouples will be installed on the duct burner liners to measure metal surface temperatures after the initial checkout testing is completed. These new thermocouples will be installed at observed hot spot locations to ensure that the average metal temperature remains at 760°C (1400°F) or less Also, a light-off detection system will be defined for monitoring the lit and nonlit condition of the duct burner. This system will be checked out during the duct burner rig testing being conducted under NASA Contract NAS3-20602.

4.2.4.5 Control Instrumentation

The control instrumentation for the testbed is indicated in Figure 4 2 4-4. This instrumentation will be used to ensure that operational limits of the F100 engine testbed are not exceeded, accounting for potential malfunction and failure modes. The pressure and temperature sensors at both the inlet and exit planes of the F100 fan will be used to help establish the inlet conditions and airflow to the duct burner for setting the desired test point

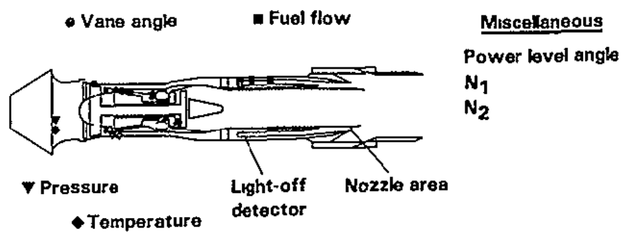

Figure 4 2 4-4 *Control Instrumentation – This instrumentation is used to ensure that operational limits are not exceeded*

Turbine meters will be used to measure all three stages of duct burner fuel flow The system for measuring nozzle area will be furnished with the F401 nozzle, including a linear variable differential transducer (LVDT) to measure the exhaust nozzle area for control.

Instrumentation is required for the control system, in addition of the bill-of-material control instrumentation used in the engine Specifically, the real time control simulation (RTCS) computer requires instrumentation to provide the inputs listed in Table 4.3.4-II.

TABLE 4.2.4-II

PARAMETERS REQUIRED FOR THE CONTROL SYSTEM

Power Lever Angle
Fan Inlet Total Pressure
Fan Inlet Total Temperature
Fan Discharge Duct Total Pressure
Fan Discharge Duct Differential Pressure
Fan Discharge Duct Total Temperature
Gas Generator Burner Pressure
Low Rotor Speed
High Rotor Speed
Fan Turbine Inlet Temperature
Stage 1 Fuel Flow
Stage 2 Fuel Flow
Stage 3 Fuel Flow
Exhaust Nozzle Area Push-Pull Cable Actuator Feedback
Unified Fuel Control Power Lever Angle Feedback

4.2.4.6 Data Validity

The validity of test data is an important consideration, and activities to ensure data validity will begin early in the design effort and continue throughout the program. Engineering specialists from the Commercial Products Division will consult with F100 performance engineers from the Government Products Division to analyze the past uncertanity of measurements accounting for sampling errors to determine the quantities of sensors at all engine stations. Uncertanity models will be made for probes, transducers and data systems so that the test data can be properly compared between tests conducted at the different sites

The ability to measure or calculate the duct burner airflow within ± 2 percent is important so that scaling parameters can be verified from duct burner rig To acquire this measurement, four methods will be considered. These are (1) duct calibration, (2) flow parameter iteration, (3) duct airflow measurement, and (4) energy balance Each of these methods will be analyzed in greater detail during the next phase of the program to determine the method or combination of methods that can best be applied to meet the program requirements. A general discussion of each method is presented below

The first method is based on a separate calibration the actual duct hardware using the F100 fan for duct flow. The duct air is calibrated, measured and a set of flow parameters are generated for the test plan. The second method is a technique currently used in F100 production engines. Basically, it involves the use of the turbine flow parameter, along with the compressor total pressure and total temperature and energy balance, to determine the compressor flow by an iterative process. The accuracy of this method is dependent on the accuracy of the turbine flow parameter. The third method, duct airflow measurement, is based on the total pressure and total temperature in a known cross sectional area of the duct However, the low velocity and thermal growth of the duct are factors that could possibly introduce large uncertainties in the final calculated flow. The energy balance method, the final consideration, is a calculation based on the thermodynamic energy balance of the engine. The test at the Government Products Division will serve to determine the uncertainty of this method which is the most promising method of duct airflow determination

4.2.5 Test Facilities

An evaluation of a number of test facilities was made to determine the sites best suited for testing the VCE testbed to meet the program objectives. As part of this evaluation, facility requirements were established. The facilities considered were: stands X-314 and X-16 at the Pratt & Whitney Aircraft Commercial Products Division in Connecticut, stands "A" and C-10 at the Pratt & Whitney Aircraft Government Products Division in Florida, the NASA-Lewis facility in Ohio, the Boeing Boardman facility in Oregon, the Rohr facility in California, and the McDonnell Douglas Quartzsite in Arizona.

4.2.5.1 Facility Requirements

The VCE test configuration, by itself, dictates certain requirements because of its size, fuel and airflow requirements. Besides the physical constraints, however, the nature of the test program presents special considerations which influence the selection of test facilities.

As structured, the planned test program is essentially comprised of three major elements. These are calibration of the F100 engine, F100/testbed checkout and emissions testing, and aero/acoustic testing. To substantiate the coannular noise benefit, special facility requirements are necessary in terms of location, terrain, and equipment Similarly, acquisition of emissions data and the calibration on the F100 engine impose certain facility requirements and considerations. Since one test facility does not have all the technical and logistic equipment for proper engine support and data acquisition, three different sites are required to complete the test program.

Several requirements were defined for conducting the F100 engine calibration These consist of. (1) defining the health of the F100 engine to be used throughout the program, (2) establishing the core and fan stream airflow necessary to assess duct burner operation and performance, and (3) providing data to update the F100 testbed simulation to accurately define the matrix of test points for the aero/acoustic evaluation.

The facility requirements for conducting the F100/testbed checkout and emissions testing are based primarily on logistics The test stand must provide easy access to test personnel as well as the sophisticated emissions measurement and service equipment for sampling NO_X, CO, THC, and smoke.

For aero/acoustic testing, the facility requirements are considerably more stringent. In addition to stand availability and necessary control and readout equipment, the facility must have the required acoustic measuring equipment. Furthermore, the geographic location of the site is a controlling factor since residential noise cannot be a constraint. Some of the pertinent facility requirements for conducting the aero/acoustic tests are briefly discussed in the following paragraphs.

The measurement surface of the acoustic field should have an acoustically reflecting paved surface that is smooth and free from waviness, similar to a commercial aircraft runway surface The surface should cover a radius of at least 30 m (100 ft) centered on the inlet flange of the test vehicle. Aft of the inlet flange, the surface should extend at least 45m (150 ft.) to the side and approximately 60 m (200 ft). A light colored surface such as concrete is preferable to avoid excessive local heating of air near the ground on sunny days.

An inlet noise barrier is required to isolate inlet fan noise. The barrier should be designed to produce a minimum of 10 dB fan inlet noise attenuation at frequencies of 250 Hz and above for over a range of angles from 40 to 60 degrees. Also, ambient noise levels in the test area should not exceed 65 dBC, and operation with community noise levels of up to 105 dB overall sound perceived level (OASPL) at a radius of 944 m (3000 ft) from the test stand must be allowable

Meterological monitoring equipment should be available to sense ambient air temperatures, wind velocity, and relative humidity. For acquiring acoustic data, both pole-mounted microphones and ground level microphones are required along with appropriate noise recording instrumentation

4.2.5.2 Test Site Selection

The test sites selected for the test program were based on cost considerations, ease of operation and test support, and data acquisition system commonality/compatibility. The three test sites selected meet these criteria and are: area "A" stands (number 9 or 10) at the Government Products Division for F100 engine calibration testing, stand X-16 at the Commercial Products Division for F100/testbed checkout and emissions testing, and the Boardman facility at the Boeing Commercial Airplane Company for aero/acoustic testing.

A description of these test sites as well as the rationale for selection is presented in the following paragraphs.

F100 Calibration Test Site

The test facility selected for the F100 calibration test is one of the test stands in area "A" at the Government Products Division in Florida. This facility was selected because: (1) a stand will be available at the desired time, (2) only minimum modifications are necessary for engine operating and instrumentation, (3) the stand has been used previously for calibration testing of F100 engines, and (4) the stand will provide the best data for correlation with other F100 engine data.

An aerial view of the test facility is shown in Figure 4.2.5-1, and a typical test stand with an F100 engine installed is shown in Figure 4.2.5-2.

The test engine will be supported in an overhead *"strongback"*, which allows the engine instrumentation to be completed prior to mounting in a test stand. The strongback supporting the engine will be attached to the stand thrust supports by four pins. Stand instrumentation will be completed by connecting multiconnector cables and pneumatic quick-connect panels to the strongback.

Figure 4 2.5-1 Test Area "A" - Aerial view of the selected test site for the F100 engine calibration test.

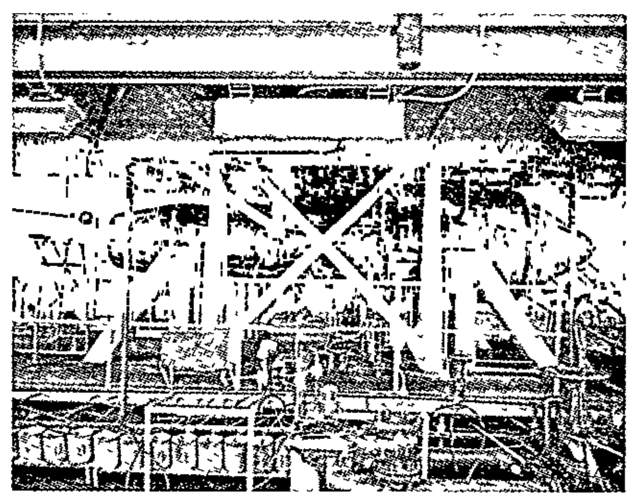

Figure 4 2.5-2 Typical Test Stand With F100 Engine Installed - Area "A" test stands at the Pratt & Whitney Aircraft Government Products Divisions are equipped with the necessary facilities for testing F100 engines since testing of these engines is done on a regular basis.

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For recording test data, a digital data recording system is used, capable of recording data from 744 inputs (384 temperatures, 240 static pressures, 96 transient pressures, 10 pulse trains (speeds or flows), 14 position indicators). The normal measurement system uncertainity is ±0.15 percent of full scale exclusive of the measurement transducer uncertainity. Specialized calibrated wire probes and sensitive pressure calibration equipment will reduce the measurement uncertainity for the performance and operating characteristic calibration.

A remote data acquisition subsystem (RDAS), a cathode ray tube (CRT), and a logging typewriter are located in the control room. These are connected to a general purpose computer (16 bit, 32,000-word core storage), located in a central recording building On-line operation of the entire system is by the test engineer using the control panel of RDAS. Digital data are converted to engineering units and pre-arranged performance calculations are made before being output on line printers and magnetic tape in the recording building and the CRT and typewriter in the test stand. The data may be processed further by another computer (16 bit, 64,000-word core storage), which is equipped with a remote graphic display system for editing data and a CALCOMP X-Y plotter for data plots.

The analog recording system consists of four subsystems transient recording with a capability of 24 pressure, thermocouple, position or switch signals and 6 speed or flow signals, dynamic pressure recording with a capability of 12 pressure signals and 1 speed signal, vibration recording with a capability of 13 vibration and/or speed signals, continuous monitor with a capability of 2 speeds, 1 flow, 1 position, 3 pressures and 1 thermocouple. The continuous monitor subsystem operates continuously while the engine is running The other subsystems are operated on command from the test engineer.

Data are also recorded manually from observation of instrumentation on the engine control console The engine operator uses this instrumentation to operate the engine within the prescribed test limits.

Testbed Checkout and Emissions Test Site

The test facility selected for checkout of the testbed system and emissions evaluation is stand X-16 at the Commercial Products Division in Connecticut. This facility, which is shown in Figure 4.2 5-3, is a gas-turbine engine test facility designed to develop both nonafterburning and afterburning turbofan and turbojet engines. Engine testing can be conducted at static sea level inlet and exhaust conditions.

The stand is constructed of reinforced concrete in the form of an elongated *"EII"* a horizontal inlet and a resonant chamber exhaust silencer with a vertical discharge stack are located at the extreme ends. Extended sound-stream type acoustical panels with 42 percent open area are installed in the inlet The test engine is attached to a suspended overheat type thrust measurement platform. Ambient air is supplied to the test engine inlet, which is isolated from the after part of the engine by a partial bulkhead. Exhaust gases from the engine are ejected into a collector tube where they are mixed with and cooled by atmospheric air aspirated over the inlet bulkhead vane. Additional cooling of duct burner engine exhaust is accomplished by injecting water into the air stream by means of spray nozzles in the exhaust duct The mixed gases are then dispersed through an exhaust silencer

The controls and instrumentation necessary to operate the engine and monitor its performance are located in the test stand control room This room is located at an intermediate elevation and a observation window is provided for a visual inspection of the test cell interior during engine operation. Test stand support equipment and services are located beneath the control room.

The test parameters are automatically recorded with the steady-state data system (SSDS). The system consists of central computer area and four remote subsystems. The central computer area consists of DDP-516 32K computer with drum memory storage There are also four 7-track 556 BPI tape units for recording stand data, 1 card punch, 1 card reader, 1 printer, and computer-subsystem interface logic. The SSDS is used primarily for engine testing.

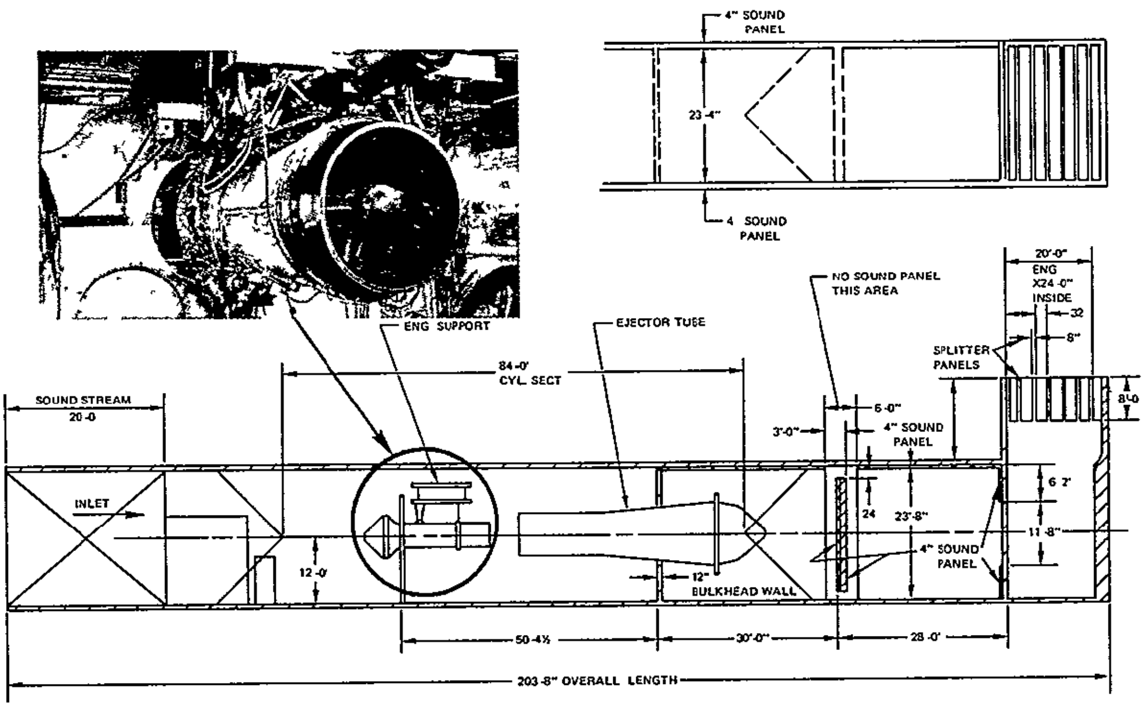

Figure 4.2.2-3 *Test Stand X-16 - This facility, located at the Pratt & Whitney Aircraft Commercial Products Division in Connecticut, has been selected for conducting the initial emissions test.*

When data acquisition is initiated, engine data are processed initially through the DDP-516 which converts the electrical signal to engineering units. The conversion to engineering units is done by a preprocessor program with information on the engine configuration supplied by input in the long term and pretest.

The engineering units can then be printed at the stand and at the central computer area, depending on thumbwheel option. In addition to printed output, the engineering units are also recorded on magnetic tape and/or cards in the standard ADR card image format. Within the DDP-516 computer, the *"quick-look"* program receives the engineering units and proceeds with its calculations to bring out (on the stand and on the central printer) the measured data, selected answers, and selected gas stream radial pressure and temperature profiles. The quick-look answers aid the engineer in evaluating engine performance during the engine run.

The magnetic tape or card output from the DDP-516 computer is hand carried to the IBM 370 for more extensive calculations by modular data reduction (MDR) programs.

Special cabling will be provided from the test cell to the control room and to an outside mobile van panel. This system provides for connecting special instrumentation such as vibration meters, pressure transducers, strain gages, closed circuit television, fuel flows, and communication. For the above purposes, ninety-four conductor shielded cables, six coaxial cables, six two conductor cables, and thirty-two thermocouple channels are installed from the test cell to the control room. Sixty-six four conductor shielded cables and ten two conductor shielded cables are provided from the test cell to the van panel.

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Aero/Acoustic Test Site

Several candidate facilities were evaluated for conducting the aero/acoustic testing. The different facilities are listed in Table 4.2.5-I, along with a summary of the results of the evaluation. As indicated, only two facilities were determined technically acceptable the Boeing Boardman facility in Oregon and the McDonnell Douglas Quartzsite in Arizona. The NASA-Lewis facility and stand X-314 were eliminated from contention mainly because of a potential community noise problem. The Government Products Division test stand C-10 was found unacceptable because of the surface condition of the acoustic field. The Rohr facility was eliminated because of availability problems and community noise concerns.

A further evaluation of the Quartzsite and Boardman facilities was made to determine a final site selection for aero/acoustic testing. The criteria listed in Table 4.2.5-II were used as a basis for selection.

Proposals from the Boeing Airplane Company and the McDonnell Douglas Company were received Their respective test facilities were judged technically competitive and comparable in cost. However, since the Quartzsite facility is new and relatively unproven, normal startup problems are anticipated. This results in a higher risk factor for the Quartzsite facility. Therefore, the Boardman facility was selected.

The Boardman test site is located on 4 x 10^8 m^2 (99,000) acres in a remote, unpopulated area some 257,440 m (160 miles) east of Portland, Oregon. An aerial view of the test site is shown in Figure 4.2.5-4.

TABLE 4.2.5-I

TEST FACILITY COMPARISON

Site	Company	Quality of Low Freq. Noise Data	Potential Community Noise Problem	Overall Stand Acceptability
X-314	P&WA (CPD)	Very Good	Probably Yes	Marginal
Boardman	Boeing	Very Good	No	Acceptable
*Quartzsite	Douglas	Good	No	Acceptable
Brown Field	Rohr	Poor (no hard surface)	Probably Not	Not Acceptable
C-10	P&WA (GPD)	Poor (no hard surface)	No	Not Acceptable
(NASA)	NASA	Undetermined	Yes	Not Acceptable

*Under construction specifically for noise testing, therefore, comments are assumptions at this time

TABLE 4.2.5-II

SELECTION CRITERIA FOR EVALUATING THE BOARDMAN AND QUARTZSITE FACILITIES

Management

- Experience with Similar Programs
- Planning
- Support in Planning this Program

Test Site

- Ease of Engine Mounting & Service
- Convenience of Services - Air, Fuel, Oil, Hydraulic
- Acoustical Surface
- Safety Facilities
- Maintenance and "Year Around" Upkeep
- Acoustically Calibrated Against Flight Noise Data

Control and "Observation" of Engine During Test

- "Block" House Location
- Ease of Monitoring Engine/Performance/Noise Parameters

Test Site Logistical Support

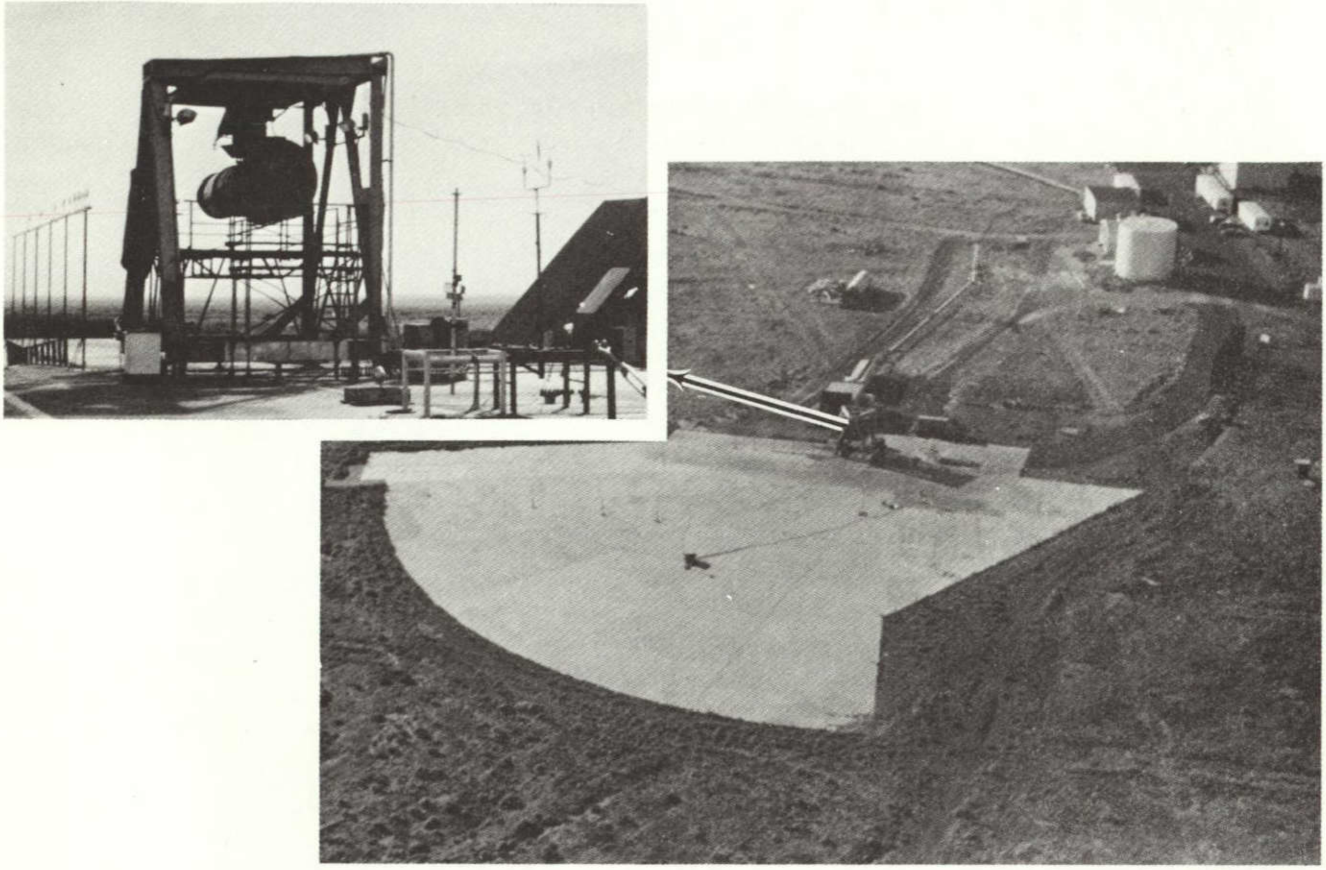
- On-Site Data Review
- On-Stand or Site Engine Maintenance/Support
- Data Handling and Transmission to P&WA
- Communication

Instrumentation

- Noise Data and System Checkout
- Operation of Data Acquisition System Requirements and Limitations
- Accuracy (Documented)
- On-Site Spares and Repair Capability

Cost

- Test
- Support



CHARACTERISTICS:
ACOUSTIC FIELD FORWARD QUADRANT TO 30 m (100 FT)
AFT QUADRANT TO 76 m (250 FT)
OPERATING FREQUENCY RANGE: 50 Hz TO 80 kHz
TEST STAND THRUST RATING: 25,000 LB

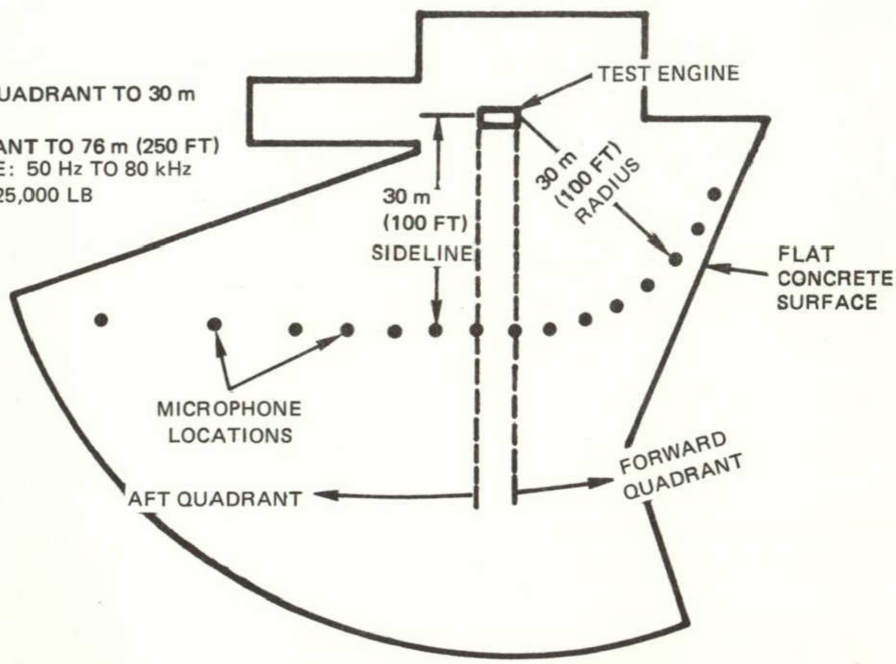


Figure 4.2.5-4 *Boeing Boardman Test Facility - This facility is located in an ideal remote area and has the appropriate acoustic field surface conditions and noise measurement equipment to conduct the aero/acoustic testing.*

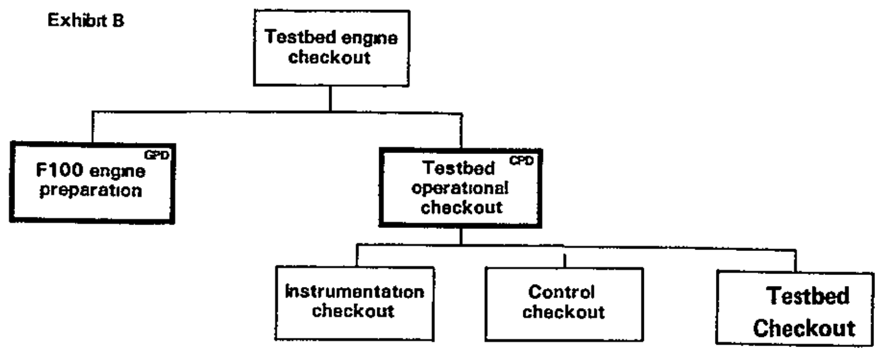


Figure 4 3 2-2 Test Plan for Testbed Engine Checkout - In preparation for the aero/acoustic testing, the F100 engine will be calibrated and an initial checkout of the testbed will be made.

checkout program involves the calibration of the F100 engine, which will be conducted at the Pratt & Whitney Aircraft Government Products Division test site "A" The engine will be tested to establish gas generator health, define the core and fan duct air flows, and provide data to update the VCE testbed engine computer simulation. The performance calibration will consist of operating the engine throughout the complete operating range, from idle to 100 percent of maximum continuous power, for complete documentation of engine operating and stress characteristics and overall aerothermodynamic behavior

The second part of the program will be the testbed operational checkout and will be conducted at the Pratt & Whitney Aircraft Commercial Products Division test stand X-16 This test will establish the overall operating characteristics of the testbed system, including controls, engine components, and instrumentation. Furthermore, potential areas of distress in the duct burner will be identified to determine operating procedures and/or additional or modified safety instrumentation for the remainder of the test program.

During this portion of the program, the emissions gas sampling system will be evaluated with respect to functional operation and reliability. Also, the laser doppler velocimeter system will be evaluated for operation and reliability.

4.3.2.2 Aero/Acoustic Test (Exhibit B)

The aero/acoustic testing that will be conducted at the Boeing Boardman test facility will provide the first acoustic test data on the large-scale duct burner and coannular nozzle testbed configuration. The test is structured to evaluate noise characteristics of the test configuration by (1) initial aero/acoustic testing covering a limited matrix, and (2) completing the aero/acoustic testing for evaluation and optimization of the coannular noise benefit.

The test consists of three major test categories, as delineated by the flow diagram in Figure 4.3.2-3 The different categories include, a facility checkout, noise assessment without the ejector, and noise assessment with the ejector.

The facility checkout at Boardman will be a brief test to check the operation of the testbed engine after testing at the X-16 test site, and to check the functional operation of the different facility service systems and readout equipment. After completing the checkout, aero/acoustic noise data will be acquired both with and without the ejector installed on the testbed.

Exhibit B

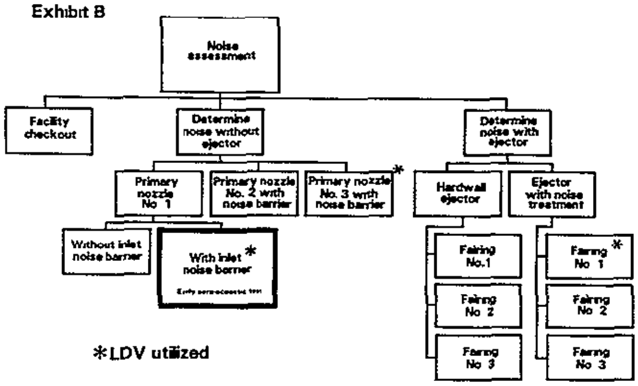


Figure 4.3.2-3 Test Plan for Aero/Acoustic Testing - A comprehensive program has been defined to acquire sufficient noise data at different conditions.

The acoustic inlet noise barrier will be used during the majority of these tests.

During testing without the ejector, early test data will be obtained to cover a selected range of test points within the test matrix. The data will be acquired utilizing primary nozzle area No. 1, as indicated in Figure 4.3 2-3. The laser doppler velocimeter (LDV) system will be employed to measure the velocity at several positions downstream of the exit planes of the core and fan stream nozzle throat. The engine will be matched three (original plus two additional nozzles) fixed-area primary nozzles to cover the complete matrix of required test points. A velocity survey will be completed with the LDV system at several locations downstream of the exhaust nozzle for two additional conditions.

Test data will then be acquired with the ejector system installed to complete the acoustic test data acquisition. The ejector will be evaluated both with and without acoustic treatment to assess the reduction in noise with an acoustically-treated ejector The evaluation will be conducted with three different aerodynamic fairings if necessary. Jet velocity measurements with the LDV system will also be taken during this part of the test.

4.3.2.3 Duct Burner Emissions Evaluation (Exhibit C)

After the noise tests have been successfully completed, the testbed engine will be returned to the Commercial Products Division for the initiation of emissions testing in Stand X-16 This is the first scheduled test to be accomplished under Exhibit C of the program. The objectives of this testing will be to obtain, as near as possible, the cruise, transonic, and takeoff duct burner operating points and to optimize the fuel flow splits for the combustion zones.

A flow diagram is shown in Figure 4.3.2-4, indicating the different types of testing that will be completed during this program. The duct burner will be evaluated in a series of tests at a number of simulated operating points to acquire the necessary test data. Essentially all of the testing will be performed without the ejector installed.

Exhibit C

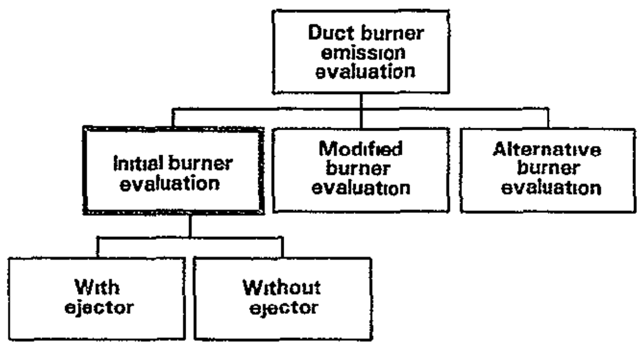


Figure 4.3.2-4 Test Plan for Emissions Evaluation - The emissions test plan includes provisions for evaluating duct burner modification as well as alternative configurations as part of the optimization process.

As indicated in Figure 4 3.2-4, tests will be conducted to assess duct burner modifications to improve liner cooling and fuel distribution using the initial liner configuration Tests to evaluate an alternate configuration defined as a result of the early testbed and/or duct burner rig program (under NASA contract NAS3-20602) will also be accomplished. A new duct liner will be fabricated for the alternate configuration.

4.3.2.4 Noise Evaluation Update (Exhibit C)

A final series of aero/acoustic test will be completed at the Boeing Boardman site using the best duct burner configuration discussed in the preceding section This test will provide data for an overall update of the duct burner and the appropriate coannular nozzle modification.

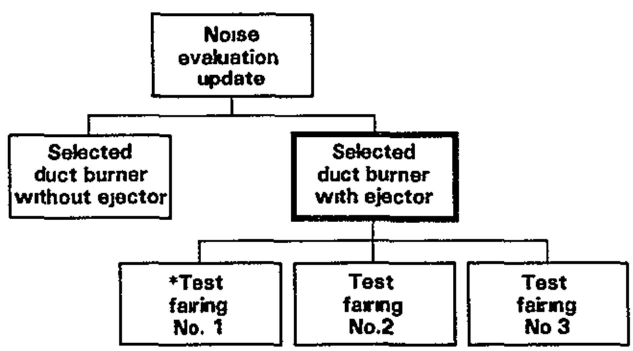
A flow diagram of the planned test program is presented in Figure 4.3.2-5. As shown, testing will be conducted both with and without the ejector. Also, testing will be performed with three aerodynamic fairings during the aero/acoustic evaluation if deemed necessary.

4.3.3 Program Work Plan Summary

An overview of the work outlined in Exhibits B and C is presented in Figures 4 3.3-1 and 4.3.3-2, respectively. These schedules delineate the major areas of effort as well as identify key program milestones. In Figure 4.3.3-1, supportive NASA-sponsored programs related to the VCE Testbed Program are listed along with the program schedule and appropriate milestones. Of main interest are the scheduling interfaces among the VCE Testbed Program, the coannular nozzle programs, and the duct burner programs.

A summary of the test plan for both Exhibits B and C is presented in Tables 4.3.3-I and 4.3 3-II, respectively. The information in these tables includes the purpose of each test, the location of the test, testbed configuration, and a general listing of the test instrumentation.

Exhibit C



*LDV utilized

Figure 4.3 2-5 Test Plan for Final Aero/Acoustic Test - Noise data will be acquired with the refined duct burner configuration for an update of the overall testbed system.

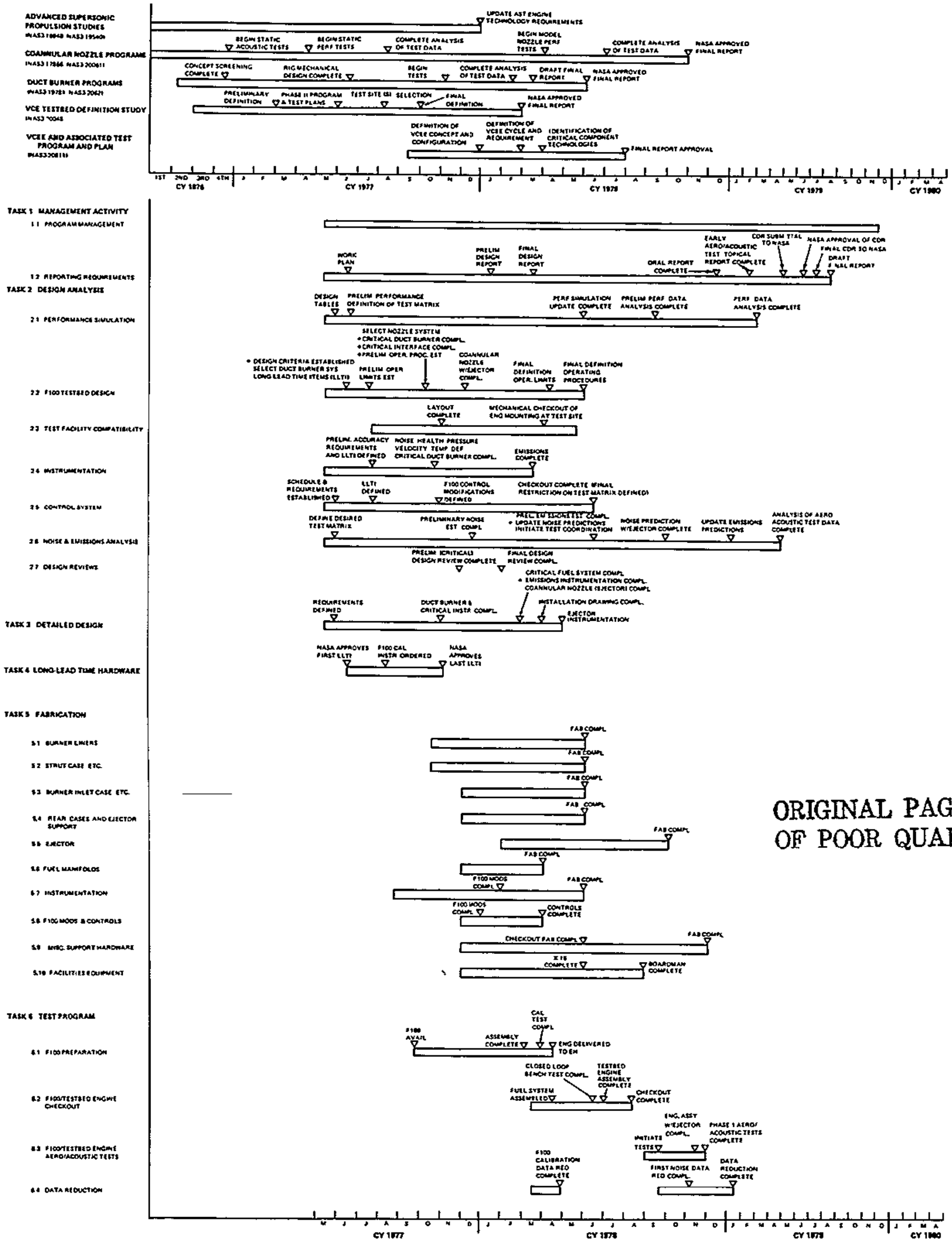


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Figure 4.3.3-1 Exhibit B - Program schedule for conducting the aero/acoustic and associated preparatory tests.

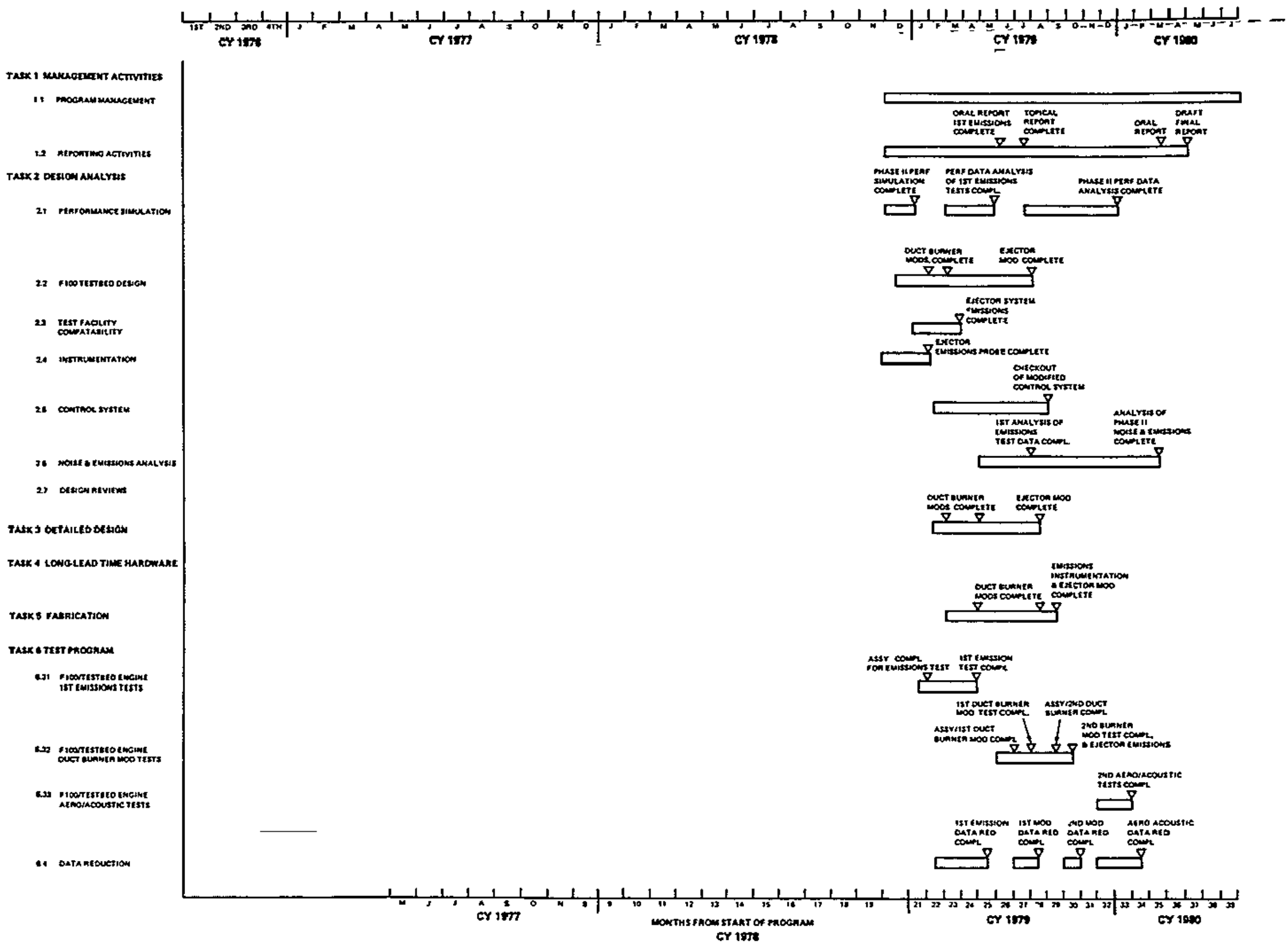

Figure 4 3.3-2 Exhibit C - Program schedule for conducting the emissions testing.

TABLE 4.3.3-I

PRELIMINARY VCE TESTBED EXHIBIT B TEST PLAN SUMMARY

Test No.	Purpose	Location	Testbed Configuration	Instrumentation
B-1	Calibration of F100 Engine to Determine Performance Characteristics	Florida	"Production Engine"	"Production Engine" + Some Experimental Instrumentation (Sta. 1 0 P_t, P, T_t, Sta. 2 5 P_t, T_t Sta. 3.0 P_t, T_t: Sta 6 P_t, T_t)
B-2	Testbed and Instrumentation Checkout	East Hartford (X-16)	Testbed with 1st Core Nozzle Area No Ejector	F100 - Same as B-1 Testbed Internal • Burner (T/C's, P_s) • Burner Inlet Rake • Accelerometers • Other Testbed External • Duct Burner Gas Sampling & P_t • LDV
B-3a	Testbed Checkout, Plus Initial Noise Test	Boardman	Same as B-2	F100 - Same as B-1 Testbed Internal - Modification of B-2 Testbed External - LDV, Microphones (1 test pt. - up to 4 axial positions with LDV).
B-3b	Completion of Noise Test Matrix	Same as B-3a	Same as B-3A 2nd Nozzle Area	Same as B-3a (Without LDV)
B-3c			Same as B-3b Except 3rd Nozzle Area	(1 test pt-each with up to 4 axial positions with LDV)
B-4a	Noise Data Acquisition	Same as B-3a	Testbed + Ejector W/O Noise Treatment	Same as B-3a Except LDV Moved to Ejector Exit (1 test pt. - with up to 4 axial positions with LDV)
B-4b	Noise Data Acquisition	Same as B-3a	Same as B-4a with Noise Treatment	Same as B-4a

TABLE 4.3.3-II

PRELIMINARY VCE TESTBED
EXHIBIT C TEST PLAN SUMMARY

Test No.	Purpose	Location	Configuration	Instrumentation
C-1a	Emissions Data Acquisition	East Hartford (X-16)	Same as B-3a, b or c of Exhibit B	Same as Exhibit B test #B-2 Except W/O LDV
C-1b	Emissions Data Acquisition	East Hartford	Same as B-4a, of Exhibit B	Tentatively same as C-1a
C-2	Emissions and Burner Performance	East Hartford	Testbed with Mod 1 Burner and Selected Core Nozzle (same lines as used for previous tests)	Same as C-1a
C-3	Emissions and Burner	East Hartford	Same as C2 except with Alternate Burner System (i e., new lines with mods from testbed and duct burner rig testing incorporated)	Same as C-2
C-4	Noise Data Acquisition	Boardman	Same and C-3 with or w/o ejector	Same as B-3a or B-4a of Exhibit B (1 test pt-with up to 4 axial positions with LDV)

LIST OF ABBREVIATIONS

A_J	Exhaust Nozzle Area (Core)
A_{JD}	Exhaust Nozzle Area (Fan Duct)
BPR	Bypass Ratio
CET	Combustor Exit Temperature
CIVV	Compressor Inlet Variable Vane
CO	Carbon Monoxide
DB	Duct Burner
EEC	Electronic Engine Control
EI	Emissions Index
EPA	Environmental Protection Agency
EPAP	Environmental Protection Agency Parameter
EPN	Effective Perceived Noise
FN	Thrust
FPR	Fan Pressure Ratio
FTIT	Fan Turbine Inlet Temperature
LDV	Laser Doppler Velocimeter
NO_x	Oxides of Nitrogen
OPR	Overall Pressure Ratio
PB	Burner Pressure
RCVV	Rear Compressor Variable Vane
RTCS	Real Time Control Simulator
SCAR	Supersonic Cruise Airplane Research
SLTO	Sea Level Take Off

LIST OF ABBREVIATIONS (Cont'd)

TCA	Turbine Cooling Airflow
THC	Total Hydrocarbons (unburned)
TOGW	Take Off Gross Weight
TSFC	Thrust Specific Fuel Consumption
UFC	Unified Fuel Control
VCE	Variable Cycle Engine
VSCE	Variable Stream Control Engine
WAT_2	Engine Corrected Airflow
WFAB	Augmentor Fuel Flow
WFDB	Duct Burner Fuel Flow
WFL	Main Burner Fuel Flow

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